NASA TECHNICAL TRANSLATION NASA TT F-16,062

REPORT OF THE WIND POWER COMMITTEE

Danske Elvaerkers Forening

Translation of "Vindkraftudvalgets Betaenkning," Danske Elvaerkers Forening, Copenhagen, Denmark, 1962

(NASA-TT-F-16062) REPORT OF THE WIND POWER COMMITTEE (Kanner (Leo) Associates) 117 p HC $5.25 CSCL 01B

N75-15154

Unclas

G3/44 07727

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 JANUARY 1975

STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TT F-16,062		

4. Title and Subtitle	5. Report Date
REPORT OF THE WIND POWER COMMITTEE	January 1975
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Danske Elvaerkers Forening	
	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No.
Leo Kanner Associates Redwood City, California 94063	NASw-2481
	13. Type of Report and Period Covered
	Translation
12. Sponsoring Agency Name and Address	14. Sponsoring Agency Code
National Aeronautics and Space Administration, Washington, D.C. 20546	

15. Supplementary Notes

Translation of "Vindkraftudvalgets Betaenkning," Danske Elvaerkers Forening, Copenhagen, Denmark, 1962

16. Abstract The report discusses the research on wind-generated electricity carried out at an experimental mill in Gedser, at SEAS' Vester Egesborg and Bogø mills, and at wind measuring stations in Gedser, Torsminde and Tune, consisting of a measuring cylinder mounted on a steel mast at elevations of 25 and 50 m. The Gedser mill is evaluated in terms of its cost and performance and is compared to other experimental mills in these terms. A system of economic models is presented which compares the costs for wind- and steam-generated electricity, with the conclusion that a wind power plant like the one at Gedser is unable to compete with a steam power plant. Wind power is however held to be useful as a replacement for imported fuel and as a power reserve to be drawn on when other fuels are in short supply. The enclosures present supplementary material on effect calculations and performance characteristics.

17. Key Words (Selected by Author(s))	18. Distribution Statement
PRICES SUBJECT TO CHANGE	Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	107	

Foreword

The question of the utilization of wind energy in this country has for some time been the subject of different investigations and considerations. Already towards the end of the 19th century, Poul la Cour began his systematic investigations into the possibility of the use of wind energy for the production of electricity by means of an experimental wind motor at Askow. Later, investigations and constructions of wind motors were carried out by, among others, the firm of Lykkegaard in Ferritslev under the guidance of Dr. Vinding and, during the Second World War, by F.L. Smidth & Co., whose largest wind motors had a sailspan of 24 m and were mounted on 24 m high towers. Besides these, several other firms constructed smaller wind motors during that war.

Most of the wind motors made up to now for electrical power generation (EPG) were made for the generation of direct current to be supplied to the smaller centers for the production of DC electricity, of which there were quite a few in this country; however, none of these smaller centers were able to utilize the full potential from the wind motors. These plants were a very useful supplement to the diesel generators normally used for EPG during the two World Wars, when it was difficult to get other fuels. The wind motors were usually designed for the greatest possible effect at the lowest possible wind velocity (3-4 m/sec) and care was taken to limit the maximum effect at the high wind velocities (greater than 10-12 m/sec), so that one attained as constant an effect as possible, which was the most sensible for the small DC generating plants. Thus, the largest type of wind motor had only a 70 kW generator.

In 1947, J. Juul, Chief Engineer at SEAS, suggested the use of wind energy for the production of alternating current to be coupled to the already existing AC network, where the wind motors were to be built such that they gave the largest possible kW production in the course of the year; in addition, one should try to attain the simplest possible construction. He further suggested the use of asynchronous generators and propeller blades designed for practically constant rpm independent of wind velocity, in contrast to the earlier constructions, where, in order to attain the largest possible effect at the low velocities, one let the wind motors work with sail tip velocities in a given ratio to the wind velocity. As a result of this, SEAS started stations in various parts of Denmark, so that they could find out how much and at what hours of the day wind energy was available. In addition, a temporary wind tunnel was constructed where roughly 30 different wing constructions and wing profiles were tested.

On the basis of these experiments, in 1950 SEAS built the Vester Egesborg Mill on Sjaelland Island (Fig. 1).

Preceding page blank

It turned out that there also was interest in SEAS's investigation outside of this organization; therefore, in 1950 the Danske Elvaerkers Forening [Danish Electricity Producers' Organization] (DEF) formed a wind energy committee consisting of representatives from the producing electricity plants which had been using wind motors and representatives of manufacturers of wind motors. Also, to investigate the possibility of using the construction of wind motor plants for the alleviation of the unemployment situation, the Labor and Public Welfare Ministry was represented. After meetings with the Ministry of Foreign Affairs, it was decided that this committee should establish contact with other corresponding organizations abroad and possibly with international organizations.

The committee consisted of the following members:

S.M. Buhl, Director, Civil Engineer, SEAS (Chairman)
W. Hanning, Director, Civil Engineerg, Frederikshavn City Engineer
J. Juul, Chief Engineer, SEAS
H. Lykkegaard, Manufacturer, Ferritslev
B. Vester, Civil Engineer, F.L. Smidth & Co. A/S
H. Raun, Civil Engineer, Labor & Public Welfare Ministry
with P. Poulsen-Hansen, Technical Secretary, DEF, as secretary.

On the basis of what was known at that point, the committee was supposed to continue the work of investigating what possibilities there were for the utilization of wind energy for the production of AC electricity, in accordance with the principle enunciated by Mr. Juul. Thus, the committee was first supposed to seek to clarify what it would cost to produce electricity by wind-driven power plants and, simultaneously, to arrive at the most comprehensive type and construction of wind motors. It was considered desirable to have a wind motor of this type built on a commercial scale.

The experimental mill in Vester Egesborg was made available to the committee.

Since the results obtained from the small experimental mill seemed to be favorable, it was thought to be interesting to test the principles on a larger experimental mill.

Since, in 1952, SEAS had taken over a wind motor for DC production that was built by F.L. Smidth and located in Bogø, SEAS had the mill changed to AC production prior to the committee's efforts to build a wind motor of the size that would be considered proper, namely, with a maximum effect of roughly 200 kW. The Bogø mill had a tower which was 22 m high and was originally fitted with a 30 kW DC generator. Since the machinery was not built to supply an output greater than 45 kW, it was fitted with a three-bladed propeller which could produce this effect at a wind velocity of about 15 m/sec. With the chosen sail profile, this corresponded to a propeller diameter of 13 m (Fig. 2).

Since the experiments with this size wind motor confirmed the results obtained at the Vester Egesborg mill, it was believed that the point had been reached, where a wind motor of the largest size that would be reasonable under the circumstances could be built. In order not to deviate too far from the familiar constructions, it was decided to have a wind motor with a 24 m propeller diameter mounted on a 24 m tower and equipped with an asynchronous AC generator of about 200 kW capacity.

Since such advanced experimentation could possibly be of public interest, on May 8, 1952, the committee -- with DEF's concurrence -- applied to the Ministry of Public Works for a grant of 300,000 kr. of the Marshall counterpart funds which had been made available for technical and scientific research. The grant was made on May 10, 1954, and the funds were designated for support of experiments related to the utilization of wind power for the production of electricity.

Relating to this grant, the Academy for the Technical Sciences was requested to be represented on this committee. The Academy for the Technical Sciences (ATV) appointed Professor A. Meldahl, a graduate engineer, Professor B.J. Rambøll, Ph.D. and Ernst von Kauffman, a Director.

In order to concentrate on the construction of the model experimental mill, a working committee was formed, consisting of Messrs. S.M. Buhl, J. Juul, A. Meldahl, B.J. Rambøll and B. Vester.

During the comprehensive project and calculation work, the committee had contact with, among others, English investigations, and thus acquired knowledge of different projects involving higher and larger wind motors, which involved several more propellers installed on the same tower.

Among the material received from abroad, there was some which related to the difference of wind velocities and to its measurement at various heights above the ground surfaces, but it was found that it was better to make an investigation of these velocities, and thus the energy distribution at various heights, under conditions corresponding to the situation in Denmark. Thus, investigations were begun on wind velocities at 25 and 50 m above ground level, and these investigations were further expanded in collaboration with the wind laboratory, three stations being established for that purpose.

The results of these investigations would not be available for some time, so the committee therefore agreed to enlarge the project based on the utilization of propeller blades located about 25 m above ground level.

On the basis of experience gained thus far, it was thought that the three-bladed propeller would give the most stable construction and the smoothest performance, and we decided on fixed propeller blades with movable flaps at the sail tips. This braking arrangement should work as a safety brake, since the wind motor's characteristics with an immovable blade and constant rpm would be such that the effect would increase with wind velocity up to a maximum value, and thereafter remain practically unchanged. The maximum output of 200 kW was chosen, and the peripheral propeller velocity of 38 m/sec corresponded to the attainment of 200 kW at a wind velocity of 15 m/sec.

With regard to the construction of towers for these mills, it was investigated whether one should prefer steel construction over reinforced concrete construction. It was found that the reinforced concrete construction was the more advantageous. From the viewpoint of labor utilization, the reinforced concrete tower would also have an advantage, since it could be built by less skilled labor. The basis for fixing the dimensions of the propellers and the other parts of the wind motor was the experience gained from the Vester Egesborg and Bogø mills, which included the effect one could expect under pulsating wind conditions.

In order to verify the calculations involved here, it was decided to determine both the bending, as well as the torsional effects, between the tower and the windmill proper.

The collaboration with the wind laboratory, just mentioned, was initiated in 1955. The wind laboratory (through Dr. Martin Jensen) took care of the instrumentation of these wind-measuring stations so that it was possible to measure the maximum wind velocities and the distribution of wind energies at the various wind velocities.

It was decided to build wind measuring stations at Gedser, Tune and Torsminde.

These stations were established in 1957. At all three stations, the measuring equipment was fixed on steel masts 25 m above ground level, and, in addition, a 50 m steel mast was installed at Gedser, in order to compare measurements at two elevations.

In 1956, a building lot was made available about 3 km north of Gedser, and the erection of a large experimental mill was begun. Construction was completed in the summer of 1957 and, after proper trials, it was put into regular service by the Minister of Public Works, Mr. Kaj Lindberg on July 26, 1954.

As already mentioned, in 1954 the Minister of Public Works had given a grant of 300,000 kr. for this committee's activities. Inflation and the acquisition of more sophisticated equipment for the scientific measurements caused the cost of the plant to exceed the grant. DEF therefore applied to the Ministry of Public Works for an additional grant of 225,000 kr. This grant was received in 1957.

The Chairman of the Wind Power Committee, Mr. S.M. Buhl, worked very actively on this committee until his death on August 21, 1958. The Secretary of the Committee, Mr. P. Poulsen-Hansen, then took over as Chairman, and, representing SEAS, H. Billeschou, a civil engineer, became a member of the committee. Mr. E. Volmer Nielsen of DEF then became the committee secretary.

An invitation from the United Nations request the Minister of Public Works to contribute to the UN Conference on New Sources of Energy, which was to be held in Rome on August 21-31, 1961. On the basis of the experimental results obtained, the following reports were made available for this conference:

"Wind measurements," by Dr. Martin Jensen;

"Construction of wind power plants in Denmark," by J. Juul, former Chief Engineer;

"Investigations at the Gedser mill," by V. Askegaard, Civil Engineer; and

"Recent developments and potential advances in the use of wind power for the production of electricity in Denmark," by J. Juul, former Chief Engineer.

These reports form the basis for what follows. The Chairman of our Committee, Mr. P. Poulsen-Hansen, took part in the UN Conference as the official representative of the Danish Government and furthermore chaired the meeting which discussed the most recent developments and potential advances with regard to the utilization of wind power.

Mr. J. Juul took part in the conference after a special invitation by the UN and helped in the formulation of the official report of the Wind Power Committee. Besides that, he wrote a personal report entitled "Economics and operation of wind power plants."

There is at this moment voluminous material available for the evaluation of the production of electricity from a plant such as that located at Gedser. The wind measuring data from there have been thoroughly research to show what production of electricity can be expected at other places in Denmark; also, it has been shown how much more output can be obtained at 50 m elevations as compared with 25 m elevations. Apart from minor difficulties at the start, the experimental mill at Gedser has worked satisfactorily so that it by and large can serve as a prototype for a more commercially produced mill, in case an interest for that should develop.

The committee has therefore concluded that there is now sufficient basis for a final report. The figures given in the final report are based on a yearly kWh production of 400,000 kWh and a plant cost of 270,000 kr.

As reported later, we have found that at Gedser it was possible to attain a 21% greater effect (per m^2 wind area) at a height of 50 m than at 25 m, but the committee has concluded that the extra cost involved in having the wind motor with a 24 m wing diameter in a 50 m high tower would be such that it would be uneconomical.

As already mentioned, DEF had been given grants from the Ministry of Public Works amounting to a total of 525,000 kr. for this committee's work. Since there grants were used during the year 1960-1961, DEF covered the extra expense of 27,279.76 kr. so that the committee could finish its work. In addition, DEF has given cost-free use of its office space and secretarial help.

The financial status of the Wind Power Committe as of March 31, 1962 is as follows:

Expenses

Gedser mill (see Enclosure 1.2 and 2.3)	378,888.81 kr.
Wind measuring stations (see Enclosure 3.7)	150,547.68 kr.
Traveling and representation expenses	9,176.05 kr
Miscellaneous	13,667.22 kr.
	552,279.76 kr.

Income

Grants from Ministry of Public Works	525,000.00 kr.
Grants for DEF	27,279.76 kr.
	552,279.76 kr.

Table of Contents

REPORT OF THE WIND POWER COMMITTEE

Danske Elvaerkers Forening

1. Gedser Mill /8*

1.1. Construction (see Appendix 1.1)

Data from the Gedser mill are as follows:

Number of sails: 3
Sail spandiameter: 24 m
Sail span area: 450 m^2
Sail tip velocity: 38 m/sec
rpm of wings: 30 rpm
200 kW generator, asynchronous with eight poles, 750 rpm
Generator slip at full operation: 1%

The mill is self-starting at a wind speed of 5 m/sec and produces 200 kW at 15 m/sec at 5°C air temperature.

The transmission between the wind rotor shaft and generator is handled by a double-chain system that has a transmission ratio of 1:25.

The reinforced concrete tower is 23 m high.

The sails, the electric installation, the transformer station and its coupling to the electrical network were done by SEAS. The machine elements and their assembly in their housing were done by Aarhus Machine Factory. The tower was planned and dimensioned by Dr. B. Højlund Rasmussen and was built by Larsen & Nielsen, general contractors, Copenhagen.

The generator produces 3 x 180 V AC, which is transformed to higher voltage and delivered to the SEAS 10 kV circuit.

The mill works automatically, and its various actions are guided by electric and hydraulic systems. The automatic system thus regulates the starting and stopping of the mill, its positioning, and the coupling and uncoupling of the generator to the network dependent on wind speed and the mill's starting and stopping. Furthermore, a number of safety measures have been devised to automatically stop the mill should any irregularities occur.

---

* Numbers in the margin indicate pagination in the foreign text.

The construction of the mill met our expectations. Certain minor changes were made after the mill had been put into regular use, but, apart from that, the mill has performed very satisfactorily. /9

1.2. Construction Costs (see Appendix 1.2)

An amount of 320,692.75 kr. was used for the construction of the Gedser mill (with the cost of the measuring cylinder excluded). These funds were drawn from the 525,000 kr. grant from the Ministry of Public Works.

1.3. Results of Performance (see Appendix 1.3)

The Gedser mill has been functioning regularly since June 1959 at all prevailing wind velocities.

From November 1959 to October 1960, the Gedser mill has produced a total of 356,920 kWh. For the calendar year 1960, it was 353,600 kWh, and in 1961 it was 339,020 kWh.

In comparing these values with the previously calculated annual production of 400,000 kWh, it is necessary to take into consideration that the mill was out of operation for 3 weeks in July 1960 because of repairs, and out of operation for 3 weeks in September 1961, for the same reason. Furthermore, the meteorological conditions during 1960 were considered abnormal, and therefore might have contributed to a somewhat lower production of electricity for that year.

Comparisons were made between the Gedser mill and the SEAS experimental mill at Bogø as to performance for 1 year. The sailspan area of the Gedser mill is 3.4 times larger than that at Bogø and should therefore have given a correspondingly greater production. The actual production ratio proved to be 5.1, which was primarily due to the fact that the wind conditions at the Gedser mill were more favorable than those at the Bogø mill.

These facts seem to emphasize how important it is to find favorable locations for wind power plants.

A comparison of production per m^2 of sailspan area from the AC mills at Gedser and Bogø with earlier DC mills at the same two locations shows that it is possible to utilize from 3.4 to 5.4 times as much energy per unit area when these plants are coupled to large AC networks, rather than to local DC circuits, since the DC plants are not able to utilize the windmill-produced energy all the time.

1.4. Financial Assessment (see Appendix 1.4)

In 1958 an arrangement was made with SEAS that concerned management and maintenace of the Gedser mill and the wind-measuring stations.

Accordingly, SEAS assumed the daily management and maintenance of the plant in return for which SEAS was to receive the plant's production, the value of which would be calculated from the current general price per kWh. /10

The financial statements for 1959, 1960, and 1961 show a profit of 2915.07 kr., and a loss of 2318 kr. and 2137.12 kr, respectively.

In evaluating these figures, it is necessary to consider that an experimental plant, when compared with a commercial plant, demands more frequent inspection, specialized measurements, etc.

The operation of the Gedser mill can therefore be assumed to be slightly more costly than would a corresponding commerically devised operation.

1.5. Operational Experience

As mentioned above, the Gedser mill was constructed, on the whole, on the basis of the experience that SEAS had gained from its experimental mills. The performance of the Gedser mill demonstrated that the design selected was correct for a plant of this size.

In the following, the operational experiences which could be of some significance for the future building of wind power plants will be mentioned.

The English research organization -- Electrical Research Assoc. -- has performed several diverse measurements and investigations at the Gedser mill. Strain gauge measurements on the sails and recording of the produced effect were some of these measurements.

As a result of this, it was found that the effect of the mill in terms of kW showed regular variations, even during constant wind velocities.

This phenomenon was further investigated at various wind velocities up to 10 m/sec.

Dr. B. Højlund-Rasmussen and Mr. J. Juul reported on this matter (Appendix 1.5.1), and it could be confirmed that the above-mentioned rhythmic variations (pulsations) would not adversely influence the mechanical system, even with wind speeds exceeding 10 m/sec. The mill was therefore put into regular use without the above-mentioned limitations of speeds over 10 m/sec, and no difficulties have occurred relative to these pulsations.

The committee conducted a series of measurements in October 1961 with the purpose of finding the reason for the pulsations observed in the effect produced by the generator. /11

The measurements were performed on the Gedser mill by means of a recording ammeter which recorded the current generated by each revolution of the mill wings.

The measurements were conducted at a wind velocity of from 9 to 17 m/sec. The windmill was turned during these measurements so that the pulsations could be measured when the mill stood in proper position with respect to wind direction and when the mill was turned 10° to the right or left of this direction.

A counting of these pulses (Appendix 1.5.2) shows that they appear with a frequency of 1.55 sec, independently of the mill's position with respect to the wind direction.

The committee therefore thinks it probable that these pulsations are due to vibrations associated with the structure of the mill and that these pulsations are actuated by aerodynamic influences.

To minimize the results of these pulsations in future constructions, one might consider a generator designed with a greater slip.

Several other valuable experiences were discovered in the following field, which are expanded on in Enclosure 1.5.3, such as:

reinforcing wires between the sails
sail braking clamps
housing for the mill machinery
lubrication system
electrical installation
technical supervision.

2. Measurements of the Overall Effects of Wind on the Gedser Mill /12

The measuring cylinder referred to earlier, which is placed between the tower and the mill housing, has the following dimensions: diameter 1400 mm, height 450 mm, thickness of material 3 mm.

The cylinder has been welded at its circular end to two plain flanges, of which the lower is fastened to the mill tower with bolts, and the upper one supports the turning mechanism that turns the mill housing. Around the measuring cylinder is installed a supporting cylinder, which can be made rigid by means of a series of conical bolts and thus takes the strain off the measuring cylinder when measuring tests are not being performed.

The dynamic forces that act on the mill are absorbed by the measuring cylinder. By applying a suitable number of resistance wire strain gauges to the measuring cylinder's surface, it is possible to measure the static, as well as the dynamic, influences and to have them electrically recorded.

Before the measuring cylinder was mounted on the mill, it was calibrated at the Denmark Technical University's laboratory for building techniques (see Appendix 2.1). After the measuring cylinder had been installed at the mill, it was rechecked to prove that the characteristics of the measuring cylinder had not changed as a result of its installation (see Enclosure 2.2).

Measurements were made at wind velocities of 10-27 m/sec. The measurements were recorded during short periods of time (around 5 sec), during which time intervals the wind velocity was assumed to be almost constant.

The measurements have shown that this mill design is not subject to unanticipated forces. There was found to be a large margin of safety for axial forces. Certain values for torsional action have been measured, which at relatively low wind velocities were close to the maximum stresses which had been predicted in the original design. These values have however not be exceeded when measured at higher wind velocities.

It should be noted that these measurements encompass relatively few values; in addition, measurements have been undertaken at only three different wind directions. It is of course possible /13
to attain more reliable measurement results by taking measurements at even more different wind velocities and different wind directions.

The committee has nevertheless concluded that it is perfectly safe to render a final report on the basis of the information gathered and, if later on there should be an interest in supplementary measurements, such measurements can be done by means of the measuring cylinder at the Gedser mill.

2.3. Cost of Construction and Installation of the Measuring Cylinder (see Enclosure 2.3)

The total expenses involved in the design, installation and use of the measuring cylinder have been 58,196.06 kr. Of this, the actual measurements have cost 30,660.10 kr.

3. Wind Measurements (See Enclosure 3.1-3.6) /14

The wind measurements mentioned here have been made from three stations, of which, as mentioned earlier, one is placed close to the experimental mill at Gedser, one at Torsminde on the west coast of Jutland, and one at Tune, which is located in the triangle of Copenhagen-Roskilde-Køge in a relatively flat terrain. At all three stations, the measuring apparatuses were placed on steel masts 25 m above the ground; in addition, at Gedser a measuring apparatus was placed on a steel tower 50 m above the ground. The height of 25 m was selected because this was the elevation of the center of the experimental mill at Gedser.

Thus it has been possible to measure the wind energy at different locations around the country and, at the same time, to compare the measured wind energy of Gedser with its energy production. Finally, it has been possible through measurements at a 50 m elevation at Gedser to estimate how much wind energy would be available for taller mills.

The measuring instruments were developed at the wind laboratory at Denmark Technical University. This equipment gives effect distribution values and indicators for maximum stagnation pressures.

The effect distribution apparatus integrates the wind energy at various velocities, which are divided up into the following six categories: 0-4 m/sec, 0-6.5 m/sec, 0-9 m/sec, 0-11.5 m/sec, 0-14 m/sec, and 0-16.5 m/sec. The choice of these six values was made on the basis of a very thorough review of existing information relative to Denmark's prevailing wind conditions.

The measurement of effect distribution is very essential in connection with the investigations of the Gedser mill, which worked at a constant rpm and whose sails are not adjustable. The effect of such a mill depends on the ratio of the sail tip velocity and the wind velocity. If the wind velocity is too great, then the angle at which the wind strikes the sails will be greater, with the result that the effect will be smaller. The measurement of the maximum stagnation pressure has as its purpose obtaining statistics for the wind's stagnation pressure for which one can determine the wind loads applicable for the design of windmills.

The measurements of the effect distributions for the calendar years 1960 and 1961 show that the mean effect per m^2 measured at Gedser at an elevation of 25 m is around 42 (kgm)/(m^2 sec). This corresponds to 3,610 kWh/m^2 per year. The sail span area of the Gedser mill is 450 m^2 and, assuming full utilization of the wind energy, this would amount to 1,625,000 kWh. The EPG of the Gedser mill for 1960 was 353,600 kWh; this would make for an efficiency of 22%. In evaluating this efficiency, it is necessary to consider that theoretically only 16/27 of the available wind energy can be used. This means that the "ideal" propeller can therefore only have an efficiency of 59%, which again means that the Gedser mill has an efficiency ratio of 37% of the "ideal" windmill. /15

On the basis of our effect measurements, we have been able to determine the maximum mean effect at 25 m elevations to be:

Tune	29 (kgm)/(m^2 sec)
Torsminde	49 " "
Gedser	42 " "

The mean effect measured at Gedser at a 50 m elevation proved to be 21% greater than at an elevation of 25 m.

Measurement of the maximum stagnation pressure has been carried on with some few interruptions since 1957.

The largest values attained at the four stations have been the following:

Tune (25), 2/21/1959: q_{max} = 51 kg/m^2 (v_{max} = 28.5 m/sec)

Gedser (25 m), 1/19/1958: q_{max} = 73 kg/m^2 (v_{max} = 34 m/sec)

Gedser (50 m), 1/19/1958: q_{max} = 81 kg/m^2 (v_{max} = 36 m/sec)

Torminde (25 m), 2/6/1961: q_{max} = 86 kg/m^2 (v_{max} = 37 m/sec)

It is interesting to note that at Gedser the ratio between the stagnation pressure at a 50 m elevation and at a 25 m elevation is 1:13. This corresponds to an effect ratio of 1:20, which is in agreement with the results of the effect measurements.

3.7. Expenses Incurred in Connection with the Installation of the Measuring Equipment and its Use (see Appendix 3.7)

The four wind measuring stations and the measuring equipment, etc. for these stations have cost 130,931.23 kr. The cost of actually conducting the measurements amounted to 19,616.45 kr.

4. Comparative Costs for Wind Power and Steam Power Electricity

P. Poulsen-Hansen, Director, Civil Engineer

In Appendix 4 we have developed some formulas and economic models for the evaluation of the conditions under which wind power would be able to compete with steam power, using cost as a basis for these considerations. We have assumed an annual interest of 6% on the capital outlays and an amortization period of 25 years corresponding to 7.82% yearly.

4.1. Wind Power

We are now introducing the term α in our wind power plant considerations. α is defined as the plant costs in kr. per kWh annual production; and to this is added the other production costs of 1 øre/kWh.

The cost of wind power electricity at the moment it leaves the plant is then

$$7.82 \times \alpha + 1 \text{ øre/kWh} \qquad (5.1)$$

Judging by the cost of the plant at Gedser of 320,000 kr., one would be justified in assuming that a corresponding plant would cost around 270,000 kr. when mass-produced; it is even possible that the price might go down to 240,000 kr.

Judging by the recorded wind measurements, those done at Gedser and at Torsminde must be considered optimal with respect to the available wind energy. When the yearly production from the Gedser mill becomes 400,000 kWh, one will get a value of 0.675 for α and, under the most favorable conditions, 0.6. If, in contrast, a wind power plant is built farther inland -- see the Tune measurements -- the kWh production will be considerably less, roughly 250,000 kWh and α will therefore be 1.08, or, under the most favorable conditions, 0.96.

4.2. Steam Power

For a steam power plant construction we have figured the building cost to be 800 kr./kW, with a reserve capacity of 25% of the maximum. Time between periodic shutdowns is 4000 hours, and fuel efficiency per kWh nets:

[Remainder of p. 16 and p. 17 missing from original]

... before such a facility will have an influence on the enlargement plan for steam power plants. /18

If wind power plants are only built on a small scale, as supplements to steam power, then the wind power-generated energy will only be used when this plant is in operation, and the question of the wind power plant's output has no meaning, because there simply is no need for that output. Therefore, the wind power energy is only of value in relation to the amount of fuel that is saved in the steam power plants (3100 kcal/kWh) with the addition of 4% loss in the primary distribution facility.

The cost for wind power ex works (5.1) must be compared with (0.31 x C)/0.96 øre/kWh where

$$7.82 \times \alpha + 1 = \frac{0.31 \times C}{0.96} \text{ øre/kWh} \tag{8.0}$$

which can also be expressed:

$$C = 24.20 \times \alpha + 3.10 \text{ kr/Gcal} \tag{8.1}$$

For $0.600 \leq \alpha \leq 0.675$ kr/kWh yearly production, the fuel price is $17.60 \leq C \leq 19.40$ kr/Gcal.

4.5. The Enlargement of Wind Power Facilities Instead of Steam Power Facilities

If wind power facilities, rather than steam power facilities, are greatly enlarged to cover the increase in electricity consumption they will, under the most favorable conditions, have to be available for use on individual days throughout the year and also during the year's maximum load, and the electricity must be able to be taken when the plant produces it.

As long as these conditions can be met, this would be possible without continuing to compare the cost of wind power (5.1) with the cost of steam power from new facilities (5.2.1).

$$7.82 \times \alpha + 1 = 2.70 + 0.25 \times C \text{ øre/kWh,} \tag{9.0}$$

which can also be expressed

$$C = 31.28 \times \alpha \div 6.8 \text{ kr/Gcal} \tag{9.1}$$

In the meantime, there is a precondition for (9.1), that is, that in addition to supplying the needed overflow electricity, the wind power plant must also be able to achieve an electrical output, meaning that there is enough electricity for use during the year's maximum load. As already discussed under Section 4.3, it would not be justifiable to determine a specific effect value below the maximum for wind power, and, as a consequence, in conjunction with the wind power facility, a reserve energy facility must be constructed, which can be called into action during those times...

[Remainder of sentence and p. 19 missing from original]

5. Conclusion

/20

Denmark is very modestly endowed with natural primary energy sources, such as fossil fuels and water power, and the country is therefore very dependent on fuel from abroad. It was therefore natural to investigate the possibilities of making this country's electrical power generation less dependent on the importation of fuel, and this was the basis for the investigations started originally by SEAS and continued by the Wind Power Commission relative to electricity production by wind power.

The resources available permitted the committee to build an experimental mill at Gedser and three wind measuring stations. The experience gained with the Gedser mill has proven that the mill works satisfactorily and that it is practical to produce alternating current and supply it directly to existing power lines. By means of the wind measuring stations it has been possible to measure the available wind energy at the different places, and thus show the significance of the placement of windmills. Concurrent measurements of wind pressure are of course of significance for the dimensioning of windmills and other structures.

On the basis of the experience gained with the experimental mill relative to building costs and production results, plus the measurements of wind energy, it has been possible to derive a good understanding of the cost for electrical energy produced by wind power plants of this type.

A system of economic models has been built, by means of which, under various parameters, a comparison has been made between the cost for wind power electricity with the cost of electricity produced by modern steam power plants.

These calculations have shown that the cost of wind power electricity corresponds to a cost for steam power electricity produced with fuel costing 17 to 19 kr./Gcal, whereas the steam power plant's fuel at the moment costs 8 to 9 kr./Gcal. It is therefore concluded that wind power electricity produced by a /21 plant of the Gedser type, under the present price structure, is unable to compete with steam power electricity. In view of this, it was considered unncessary to investigate whether the wind power electricity could compete with water power electricity.

Wind power might be valuable as a replacement for the importing of fuel and could be considered as a reserve to be drawn on in situations where fuel would be in short supply. Further calculations show however that the necessary investments would be of such a magnitude that a project like this, at this time, would be inappropriate.

It should be emphasized however that the building of wind power plants would require a considerable amount of Danish labor and therefore could help alleviate a poor employment situation; thus, one might apply the same point of view to the building of wind power plants that one might apply to reclaiming arable land.

It can furthermore be stated that at the UN conference on new energy sources in Rome, August 1961, where this committee had given information on its research activities, it was found that a number of emerging nations showed a great interest in the Danish work with wind energy. Thus, there should be good possibilities for Danish industry, if they were interested, to take part in the delivery of wind power plants to emerging nations.

The devised economic models will be of general usefulness under the given assumptions and will make it possible to review the problem in its technical-economic aspects, if future developments would cause an essential change of the figures on the basis of which the majority of the committee drew their conclusions.

May 1962

H. Billeschou	W. Hanning	E. von Kauffmann
H. Lykkegaard	A. Meldahl	P. Poulsen-Hansen
B.J. Rambøll	Herluf Raun	Børge Vester

Mr. J. Juul, Chief Engineer (Retired), has declared himself to be in disagreement with the other members of the committee in regard to the assumptions and evaluations referred to in Section 4, "Comparative Costs for Wind Power and Steam Power Electricity," /22 and the corresponding Enclosure 4, "Considerations Concerning the Competitive Power of Wind Generated Electricity as Opposed to Steam-Generated Electricity," and has therefore been unable to agree with the above conclusion.

Enclosure 1. The Gedser Mill, former Chief Engineer J. Juul /23

1.1. Construction

The construction of the Gedser mill was completed during the summer of 1957. After the mill had completed its trial run together with subsequent adjustments and minor modifications, and after various measurements of effect and machinery were adapted, the mill was put into regular operation in June 1958. It has since that time, for all practical purposes, been in operation day and night in connection with SEAS' electrical network, and no calamities of any consequence have occurred.

The construction of the Gedser mill was based on the research and experience of SEAS and their research stations at Vester Egesborg and on Bogø.

The sails, the electrical equipment, the transformer station and its coupling to the electrical network were made by SEAS. The machine elements and their assembly in their housing were erected by Aarhus Machine Factory. The tower was planned and dimensioned by Dr. B. Højlund Rasmussen and was built by Larsen & Nielsen, general contractors, Copenhagen.

Data from the Gedser mill are as follows:

Number of sails: 3

Sail span diameter: 24 m

Sail span area: 450 m^2

Sail tip velocity: 38 m/sec

rpm of the sails: 30 rpm

Generator: 200 kW, asynchronous with 8 poles, 750 rpm

Generator slip at full operation: 1%

The mill is self-starting at a wind speed of 5 m/sec and produces 200 kW at 15 m/sec at an air temperature of 5°C.

The transmission between the wind rotor shaft and the generator is handled by a double chain system that has a transmission ratio of 1:25.

The mill is 25 m high.

In the following will be given a description of the essential details of the mill's construction.

1.1.1. The Tower /24

The complete mill construction is shown in Fig. 4, and it shows how the sails are guyed and how the machine elements are placed on the tower. The tower consists of a vertical tube (1) made of prestressed concrete, while the support ribs (2) and the foundation (3) are made of reinforced concrete. The previously mentioned measuring cylinder (4) is placed between the machine elements and the tower. There is a platform (5) which can be reached by both an inside and an outside ladder (6).

At the side of the tower is a transformer housing made of steel.

1.1.2. The Sails

As a result of research in the SEAS experimental wind tunnel, the sail profile proved to be favorable (Fig. 5). Fig. 5 also indicates that a three-sail windmill with this particular sail profile is efficient and that the windmill has this value or efficiency when the sail tip velocity is 5-6 times as great as the wind velocity.

Curve 1 on Fig. 6 indicates how many times a year various wind velocities occur. These measurements of wind energy were made by SEAS in South Sjaeland. Curve 2 gives the total amount of energy produced during the year; this amount is greated at 8 m/sec. Since windmills which are coupled to asynchronous AC generators in connection with a large AC network have to run at an rpm that only varies in accordance with the generator's slip, which normally is from 1 to 4%, it is necessary that the rpm and the sail tip velocity be chosen so that they take the best advantage of the largest yearly wind energy, which, in this particular case, is 8 m/sec. Since the mill has its greatest efficiency when the sail tip velocity is about 5 times as great as the wind velocity (see Fig. 5), it was concluded that the sail tip velocity should be 38-40 m/sec.

Under different wind conditions than those that exist in South Sjaeland, it might possibly be advantageous to adjust the transmission between the sails and the generator so that the sail tip velocity is either greater than or less than 38 m/sec. In addition, one would have to take into consideration whether one wishes to have greater output spread over fewer hours or less output over more hours of the year. In both cases it appears that the wind energy will be about the same, but of course this depends on whether the wind energy occurs as a strong blast during a few /25
hours of the year or whether it occurs as a daily light wind.

The mill's output indicated by Curve 2 in Fig. 7 can be constructed using the relationship shown in Fig. 7 between the wind's power (indicated by Curve 3) and the mill's efficiency (indicated by Curve 1); or, if the mill's output curve is known, the efficiency curve can be worked out in the same manner. It can be seen that the mill's output curve falls off at a wind velocity of 15 m/sec. This is due to a phenomenon called stalling.[1] Stalling occurs when the wind's angle of incidence to the sail becomes too great. The wind therefore spills off the sails adversely, and the mill's output will become comparatively less as the wind velocity increases.

With the SEAS constructed research mills, the stalling phenomenon is the major method used to prevent overcharging during a storm. Normal changes in the wind produce fluctuations in the mill's output, which can be readily absorbed by a large electrical network.

In the meantime, the mill should be able to be stopped whenever lubrication and maintenance are necessary, or when there is a break in the connection with the electrical network. In the special case of braking, the flaps at the ends of the sails are brought into play. This is shown in Fig. 8.

The braking flaps (1) comprise 12% of the sail's surface and are, under normal conditions, integral parts of the sails. The braking flaps are secured to a shaft (2), which, through the use of the mill's automatic mechanisms, can be extended 300 mm in the sail's longitudinal axis through a tube located in the main part of the sail. With this motion, the braking flaps are in opposition to the rest of the sail, bringing the mill to a standstill. The braking flaps are moved by a hydraulic servomotor (5) in connection with the mill's automatic system.

The sail's bearing girder (4) is rectangular in shape and is welded together from 10 and 16 mm thick steel plates. The girder's dimensions vary from the hub to its outside end, as shown in the drawing. Layers of flat iron are attached to the girder and to these layers are attached streamlined cross ribs made of wood. In addition, wooden moldings are placed on the sail's front edge and near its back edge.

Sheets of light metal 1 mm thick are fastened to the rib system /26 by means of galvanized flathead screws and thus the streamlined form of the sail is fashioned so that the front side of the sail has a bevel of 3° at the braking flap and 16° at the sail's base.

Through their research in the wind tunnel, SEAS found that this bevel is the smallest which allows the mill to be

---

[1] The same situation occurs in connection with the wings of airplanes. Stalling can in this case result in a catastrophic reduction of the airplane's carrying capacity.

self-starting at about 5 m/sec wind velocity, and, at the same time, it gives the sail its largest possible forward motion.

When a sail is constructed as described above, it must be looked at in light of the fact that it was only possible to make the sail by hand. It will eventually become cheaper to mass produce a larger number of sails in the form of a shell construction made of precut welded steel plates, which could be fastened to the mill's hub by means of flanges. It is also possible to build sails of other materials than steel, for example, plastic, if this becomes economically feasible.

The wind's pressure and its mechanical influences on the sails are dependent on the sail's relative strength in relationship to the wind velocity. On the basis of the experienced gained at the SEAS Vester Egesborg mill, when evaluating the Gedser mill, it was decided to begin with a wind pressure of 15 t for the Gedser mill.

As a result of variations that can occur in the wind's velocity within a general distance of 24 m, calculations were made of the torque influences which can occur around the vertical axis of the mill's tower. This torque moment was found to be 7200 kgm which, together with the above-mentioned axial influence, is the basis for the calculations of the dimensions of the sails, the machine housing, and the tower.

The calculations show that, for all practical purposes, it was impossible to build an aerodynamically favorable sail profile of steel that was freely suspended from the hub without guying. The sails are therefore constructed to include guys which absorb the axial pull and which relieve the back and forth bending moments of the sail girder due to the sail's rotation.

In the calculations it is figured that steel construction has 600 kg/cm^2 as a maximum for variable standard influences and 200 kg/cm^2 when the influences change direction because of the rotation.

1.1.3. Machine Elements /27

The construction of the machine elements is shown in Fig. 9. The sail girders (1) are screwed to the wing hub (2) into which ball bearings (3) and (4) are built. The ball bearings cannot be replaced without taking down the wings and the hub. The carrying support is dimensioned very generously, so that, according to the calculations, it has a long lifetime. Thrust bearing (3) can be replaced without taking down the wings and the hub, whose support is dependent upon a bearing on the axel shaft (5), which is firmly fixed to the machine housing and is bored through. The resulting canal (6) works as the oil pressure connection to the hyraulic servomotors, which place the sail's braking flaps in the position to allow the mill to operate.

An oil-tight bushing (7) is placed between the oil canal in the axle shaft and the rotating oil pipe system in the wing hub. A metal plug, which melts at 110°C, is used as a safety valve (8) in the axle shaft's high pressure oil canal. In case of overheating of the axle shaft due to a fault in the bearings, the plug will melt, the oil will spill out, and the mill will stop.

Based on the experience SEAS had at the Vester Egesborg mill and at the Bogø mill, the possibility of using a gear wheel that was dimensioned for the transmission of the 200 kW output at 30/750 rpm was investigated for the Gedser mill. However, it became apparent that, under the circumstances, this type of gear was inordinately expensive; therefore, it was decided to use a roller chain gear, which would bring about the same results.

The gear consists of a two-part chain wheel (9) that is attached to the hub which, with the help of two identical but independent 2-1/2" chains (10), pulls the chain wheel (11) on the second axle (12). This second wheel has a triplex chain wheel (13), which has attached to it three identical but independent 1-1/2" chains (14), which pull the generator's shaft (15). This second shaft is connected to the generator (16) by means of an elastic coupling (17) that has a shear pin (18), which snaps in case of relay failure, which could lead to an incorrect coupling of the generator to the electrical network, and, thereby, cause a dangerous shock to the machine parts and the sails.

The bearing supports (19) and (20), together with the hydraulic pumping system (21) and the generator are mounted on a welded steel plate base (22). The yaw ring (23) is attached to the bottom of this base. The yaw ring is of normal construction which uses... [remainder of paragraph missing in original document].

The inside immovable ring is shaped like a tooth /28
rim, and these teeth are meshed with the gear of the yaw motor. Built into the gear is a worm drive which locks the gear to the yaw ring when the yaw motor is stopped. This is steered automatically by a wind vane (24), which is on top of the machine housing. There is access to the machine elements from the platform of the tower by means of a ladder (25), which leads to an opening in the shelf. The internal parts of the yaw ring are fixed to the mill's tower by means of a 450 mm high measuring cylinder (26), on which there are placed strain gauge elements. By means of these elements and their connected measuring instruments, the mill's axial influences and torque influences can be measured. The measuring cylinder is lightly built, in order that it be as sensitive as possible.

An additional cylinder is therefore placed around the measuring cylinder; this cylinder is more sturdily built and equipped with junction gussets (28) that grip the cam in the shelf plate, and the cylinder is secured to this. Loosely fitting conical bolts in the junction gussets and the cam take up the strain when measurements are not being taken by the cylinder.

The chain wheels and the chains are surrounded by a casing. The primary chains are lubricated by means of an oil bath, while the secondary chains are lubricated by means of an oil pump on which there is placed an oil pressure relay, which stops the mill if the oil pressure ceases. In order to prevent the oil from spilling out and rainwater from seeping into the primary chain box, a labyrinthine seal (29) is placed in between the nonmoving and the rotating part.

The elastic coupling (17) is in the form of a shell which has an outside band that is used as a mechanical brake. The braking blocks are raised when the oil pressure acts on the hydraulic system at the start of the mill; when the mill stops and the oil pressure ceases, the braking blocks are pressed on the braking band by a weighted arm. This brake will however not stop the mill -- that occurs by means of the sail's braking flaps -- but this mechanical brake can hold the sails solidly when the mill needs to be worked on.

All the machine elements are enclosed in a galvanized steel housing on top of which is placed a wind vane (24). The wind vane is mechanically connected with a relay that activates the turning motor.

The cables to the generator and the pilot cables are led to the machine elements through a rubber pipe (30), which is attached to the base of the machine housing. This rubber pipe is suspended freely in the tower so that it can easily turn 10 revolutions in each direction.

Thus, the use of brushes for the connection of the circuit /29
to the machine elements is averted. Experience shows that the turning of the mill amounts to about 10 revolutions in the direction of the sun yearly.

1.1.4. Mechanical and Electrical Functioning of the Gedser Mill

The mechanical and electrical functioning of the Gedser mill is shown in Fig. 10. The mechanical portion is shown schematically, and the wires to the generator and the yaw motor are shown as a single line, in order to make the diagram easy to read.

When the mill starts, the high-tension breaker (31), the low-tension breaker (28), and the pilot cables breaker (41) are closed.

The electromagnet (15) will then close the valve (16), and the electrical motor (19) and the oil pump (20) will start operating and putting pressure on the hydraulic system. As a result, the servo motor (5) will pull the braking flaps (2) on the sails (1) into an operational state in which the braking flaps become an integral part of the sails. In addition, the servomotor (7) will release the mechanical brake (6) on the axle leading to the generator (8). As long as the wind velocity is 5-6 m/sec, the mill will start; and when the eight-pole generator has reached 750 rpm, the centrifugal relay (9) will close the contactor (24) and connect the network to the generator, giving energy to it when the wind velocity is greater than 5 m/sec. If the wind velocity drops below this value, the generator will take its energy from the network and the return current relay (26) will then disconnect the current to the coupling magnet in the contactor (24). This will cut the generator from the network until the wind once again reaches a velocity of more than 5 m/sec, and then the centrifugal relay (9) will once again couple in the generator. At the SEAS' research facility, the Vester Egesborg mill and the Bogø mill, the generator's slip was 5% and 4%, and it was possible to obtain necessary selectivity between the centrifugal relay and the return current relay.

At the Gedser mill, however, the generator slip was only 1% at full load, and the centrifugal relay could not break the connection to the generator's contactor with any degree of exactness when the return relay had functioned. It therefore became necessary to include a dampening contact, which slowed it down so that the contact to the centrifugal relay was not closed before the relay, responding to the mill's decreased rpm, had been able to break the connection to the contactor's coupling magnet.

The mill is stopped by disconnecting the low-tension circuit breaker (28) or the pilot cables circuit breaker (41). The connection to the contactor (24) will therefore be cut off, as will the generator's connection to the network. At the same time, the /30
connection to the holding magnet (15) will be cut off. As a result, the valve (16) will open and remove oil pressure to the servomotor (5 and 7), and will put into operation both the braking flaps on the sails and the mechanical brake (6), at which point the mill will stop.

In order to hold the sails in the correct position with respect to the wind's direction, the wind vane (37) is used, and it is connected to the mechanism that controls the sail's positioning (38). The wind vane can cross two phase wires that lead to the yaw motor (36), so that it changes its rotational direction as the wind shifts direction from right or left. When the wind hits the sails at a right angle, the mill holds its position by means of a worm drive in the yaw motor's gearbox. The movements of the wind vane are restrained a little by means of a shock absorber filled with oil.

There are various safety provisions for stopping the mill in case of damage or when the electrical connection to the mill is cut off.

If such a break occurs, so that the generator does not become magnetized by the electrical network, then the contactor (24) will disconnect as will the holding magnet (15), and, as a result, the oil pressure will cease, and the mill will be stopped by the braking flaps and the mechanical brake.

If there are condensers of the necessary capacity in this portion of the electrical network, which stay connected to the mill's generator, the generator will become magnetized. If the load is larger than what the mill can take care of, the turning speed will go down, the output voltage will fall and eventually ease. On the other hand, if the load is less than what the mill needs, the turning speed and the generator's voltage will increase.

The overvoltage relay (39) will then disconnect the pilot cables, if this has not already been done by the centrifugal relay safety contact, which can also disconnect the pilot cable; and the same can occur by means of a relay operated by a pressure cylinder 21 [sic] that is part of the hydraulic overpressure system.

In the holding magnet (15) plunger, a spring is built in so that the valve (16) can also function as a safety valve, which opens up in the event of overpressure on it. As a result, the sail's braking flaps will prevent the occurrence of dangerous situations due to the excessive rpm. Thus, this is made safe by many means.

The various safety devices lock themselves if they have been /31 set in operation, so that the mill cannot be started before they are manually disengaged, and only one of these devices need function to bring the mill to a standstill.

The wires from the transformer room to the base of the machine housing travels through a rubber pipe (32) in the tower. To this is attached a string at the top of the tower which can operate a seesaw relay through a pulley system, in the event that the turning mechanism turns the machine housing more than 10 rotations. In this case, the pilot cables will be shut off, and the mill and the turning mechanism will be stopped by the seesaw relay (34), which is connected to a falling weight (35). In the event of abnormal shaking in the tower, the weight will fall down from its position and thereby cause the seesaw relay to stop the mill.

Normally, the generator cannot be overloaded even in the strongest hurricane because the mill's output is automatically curtailed by the sails' "stalling" during strong winds.

If there were a break in the wire network in phase t, the generator's operation in phases r and s could be overloaded; therefore, an excess current relay (25) is added, which, in such a case, would disconnect the pilot cables and stop the mill. The relays (25 and 26) and the kWh-meter (40) work in connection with the current transformer (42) in the main cable.

The Gedser mill's pilot cables are in substance the same as the ones at Vester Egesborg and Bogø. At Bogø there is, instead of a hydraulic regulating system, a strong coil spring that, with the aid of a winch or an electromotor, tightens and holds in the sails' braking flaps when the mill is in operation. At the Vester Egesborg mill, compressed air is used instead of oil pressure. The condensation of water can occur within the system, which is particularly unfortunate during frost weather; however, all three systems are able to function so that no accident of any consequence occurs.

1.2. Construction Costs

The list below covers the costs which only relate to the planning and construction of the Gedser mill (the cost of the measuring cylinder is excluded).

The total construction costs as shown are 320,692.75 kr. It has to be taken into consideration that the sails, the electrical system and the transformer station were made by SEAS under advantageous conditions.

Cost as of March 31, 1962 /32

Tower, including the soil investigations and the building lot	kr.	76,400.33
Machine elements (including its mounting)	kr.	75,000.00
Sails and the propeller hub	kr.	44,135.57
Chains, holding brake, hydraulic brake lifter	kr.	20,423.63
Generator, transformer, distribution system	kr.	56,765.55
	kr.	272,725.08
Planning: sails, transformer and tower	kr.	47,967.67
Total	kr.	320,692.75

1.3. Operational Results

Former Chief Engineer J. Juul.

The Gedser mill was put into regular operation in June 1959, and has since that time delivered electricity to SEAS' 10 kV electrical network.

In the following, a comparison is shown between the annual production taken at the same time between the Gedser mill and SEAS' research mill at Bogø (Table 1).

TABLE 1

	Gedser mill (200 kW) Sail span area 450 m^2 kWh	Bogø mill (45 kW) Sail span area 132 m^2 kWh	Proportion $\frac{450}{132} = 3.4$
1959 Nov.	25,710	6,324	4.06
Dec.	52,840	11,000	4.80
1960 Jan.	31,460	8,165	3.86
Feb.	44,640	8,487	5.27
March	34,180	5,431	6.30
April	38,340	6,757	5.68
May	27,390	4,425	6.17
June	23,980	3,588	6.66
x) July	22,000	4,324	5.10
Aug.	18,920	3,798	5.00
Sept.	20,840	4,165	5.00
Oct.	30,740	6,195	5.00
I	371,040	72,659	5.1

x) In July 1960, the Gedser mill was stopped for 3 weeks because of a problem in the yaw mechanism. Production was therefore actually only 7880 kWh during that month; however, based on the proportional relationship in production between the two mills as shown in the last column of the table, the production would have been 22,000 kWh, which is used as the production for the Gedser mill for the month of July, for the sake of the comparison of the annual production of the two mills.

Both mills start at a wind velocity of 5 m/sec.

The daily production of the mills is figured in kWh at 9:00 a.m. daily, monthly and yearly. The production represents the period from 11/1/1959 to 10/31/1960.

The proportional relationship between the sail span area of the two mills is as 450 is to 132 or 3.4 [sic]. However, the yearly average of the productions is 5:1, which first and foremost is due to the fact that the wind conditions are most favorable at Gedser, where the mill is located on the southern tip of the west coast of Falster. Bogø, on the other hand, is located on a small sound between Sjaeland and Falster and, as a result, has about the same wind conditions as inland areas. /33

The yearly production for the Bogø mill since 1952 is shown in Table 2.

TABLE 2

	Bogø mill Production kWh	kWh/m^2
1953	87,170	660
1954	90,967	690
1955	68,680	520
1956	91,133	690
1957	78,191	590
1958	78,502	590
1959	76,363	575
1960	72,659	550
	643,665	

The Bogø mill's average production for the above-mentioned 8 years was 80,400 kWh/year, while the production in 1959/60 was 72,659 kWh, or 10% lower than the average. This was due to the meteorological conditions in 1959/60, in which the wind was westerly with a small velocity for an unusual number of days.

It is also likely that the Gedser mill's production for the year 1959/60 was comparatively low and that the mill's normal year yearly production -- as calculated -- would be about 400,000 kWh. If the Bogø mill's yearly average production were recalculated, based on the 5:1 proportional relationship, one would find that the Gedser mill's average yearly production should be 410,000 kWh.

The calculations show that the Gedser mill will, on an average, yearly produce about 300 kWh per m^2 more sail area than the Bogø mill, which shows how important it is to find the most favorable places for the setup of wind power facilities. /34

Experience in the technical area from the Bogø mill is however, to some extent, weighted in favor of showing a greater effectiveness for the Gedser mill.

Both at Bogø and at Gedser, there have been wind power facilities since 1942, which generated DC current in connection with the local diesel-driven DC plants.

Both of these DC mills were of modern construction with streamlined sails. In order to keep a constant tension on the DC plants, the mills were equipped with mechanical elements that regulated the output. The mills were used to their greatest capacity, because, during the war, there was a great shortage of diesel oil.

Table 3 shows the mills' production for the years 1943-1946.

TABLE 3

	Gedser DC mill		Bogø DC mill	
	kWh	kWh/m^2	kWh	kWh/m^2
1943	135,671	300	29,220	122
1944	125,800	280	28,000	117
1945	117,100	260	31,889	132
1946	113,640	252	20,882	83
	492,211		109,991	
Yearly average	123,000	272	27,500	114

The table shows that the average production per m^2 sail span area was respectively 114 and 272 kWh yearly, and that, under the given local wind conditions, from 3.4 to 5.4 times as much energy per unit area can be utilized when the wind power facility is connected to the larger AC network rather than to the local DC facility. The reason for this is that the AC network is capable of absorbing a much larger portion of the mill's possible production without affecting the local electricity network's voltage conditions.

1.4. Financial Assessment

In 1958 an agreement was made with SEAS involving the maintenance of the Gedser mill and the wind measuring stations.

The agreement was as follows: /35

Section 1. SEAS would take care of the operation and maintenance of the research facility, including the inspection, lubrication, cleaning, and insurance.

Section 2. SEAS will supply the manpower and materials in the event that machine elements in the research facility need to be replaced.

Section 3. In accordance with the Wind Power Committee findings, SEAS will conduct the operational procedure for the research facility and prepare the yearly report for the Wind Power Committee, just as SEAS will assist with carrying out and completing the research.

Section 4. Together with the Wind Power Committee, SEAS will assist in presenting the research facility for study visits from within Denmark and abroad.

Section 5. SEAS will cover the costs of Sections 1-4.

SEAS will figure the costs of Sections 1-3 in the following manner:

a. The cost for wages and materials will be based on the actual unpaid wages and materials plus 12-1/2% for administration.

b. The cost of running the mill will be figured on the current cost for SEAS without adding the cost of administration.

c. The supervisory personnel's wages will not be debited.

For costs under Section 4, SEAS will figure the net outlays for consumption and the like, while nothing will be figured for operation and for supervisory personnel.

Section 6. As compensation for its efforts, SEAS will obtain the research facility's electrical production, whose value will be based on the quarterly production multiplied by the quarterly operational costs per kWh.

Section 7. When the Wind Power Committee has finished their research and measurements at the research facility -- presumably in 2 years -- negotiations will be carried out between SEAS and the Wind Power Committee for the eventual takeover of the research facility by SEAS.

Section 8. The present agreement can be terminated by both parties with 1 year's notice in writing.

If it should happen that there develops an unreasonable difference between SEAS' costs and their compensation, a new arrangement regarding Sections 5 and 6 of the agreement can easily be worked out. /36

October 29, 1958

Danish Electrical Producers' Association Jens Møller, Chairman of the Board	Southeast Sjaeland Electricity Corporation Viktor Hansen, Chairman of the Board

Financial assessments for the years 1959, 1960, and 1961 are listed below.

Capital Outlays	1959	1960	1961
Materials	2,421,49	3,315,23	1,996,16
Wages	1,310.54	2,826,99	3,035,77
Administration	466.52	910,47	954,49
Mill operation	807.48	1,612,40	1,402,85
Rental of additional space	400.00	400.00	400,00
Mill maintenance	1,200.00	1,300.00	1,250,00
Capital outlays from Section 4	321.80	151,90	255,70
Miscellaneous	0.00	4,391.55	4,963,74
	6,927.83	14,908,54	14,258,71
Income			
Production			
213,930 kWh	9,842,90		
353,600 "		12,590,54	
339,020 "			12,121,59
Surplus	2,915,07	÷2,318,00	÷2,137,12

It must be taken into consideration when evaluating the financial assessment that a research facility in contrast to a commercial facility needs frequent attention, frequent reading of measurements, and extensive study of any breakdowns. The capital outlays for the Gedser mill therefore easily become substantially higher than would be the case for a similar commercial facility.

1.5. Operational Experience

1.5.1. Research Concerning the Pulsations in the Effect of the Gedser Mill

Dr. B. Højlund Rasmussen, Civil Engineer

[Beginning of first paragraph missing from original document] ... and the current analysis is trying to determine whether these /37 pulsations are related to the corresponding or the eventual larger oscillations in the mechanical aspects of the mill's elements and, if possible, to explain the beginning of the oscillations.

An analysis of this is shown in Fig. 11, and it shows the main features of the system that gives the mill its working pattern.

Mass inertia moment I_1 corresponds to the propeller, and, together with a flexible axle with spring constant k_1 tm/rad, is connected with a mass inertia moment I_2, which represents a gear wheel, chain, etc. in the mill. I_2 is connected to the generator at an axle with a spring constant k_2, which is characterized by the inner damping c_3 tm sec/rad.

In that the position of I_2, I_1 and the generator's rotor is constant with the angles ϕ_1, ϕ_2, ϕ_3, the system's equation of motion is the following when the propellers are influenced by a drive moment M_v from the wind.

$$M_v - I_1 \ddot{\varphi}_1 - k_1 (\varphi_1 - \varphi_2) = 0 \tag{1}$$

$$k_1 (\varphi_1 - \varphi_2) - I_2 \ddot{\varphi}_2 - k_2 (\varphi_2 - \varphi_3) = 0 \tag{2}$$

$$k_2 (\varphi_2 - \varphi_3) - c_3 (\dot{\varphi}_3 - \dot{\varphi}_0) = 0 \tag{3}$$

Equation (3) indicates that the generator's stopping moment, which holds a balance with the moment in the axle between I_2 and the generator, is proportional to the difference between the rotor's angular velocity $\dot{\phi}_3$ and a certain constant angular velocity $\dot{\phi}_0$.

Here $\dot{\phi}_3 - \dot{\phi}_0$ is very small in comparison to $\dot{\phi}_0$.

The given effect is E kW = $E \cdot 0.102$ tm/sec = $Mg \cdot \dot{\phi}_3 \approx Mg\dot{\phi}_0$; where Mg is the moment in the axle between I_2 and the generator.

$$M_g = c_3 (\varphi_3 - \varphi_0) = \frac{0.102\ E}{\dot{\varphi}_0} \tag{4}$$

If one now labels E as a function of time t, from (4) one could determined ϕ_3, and, thereafter, ϕ_2 with the aid of (3), ϕ_1 with the aid of (2) and M_v with the aid of (1).

The mechanical influence of the mill is, between I_2 and the generator, proportional with Mg and, between I_1 and I_2, proportional with $M_v - I_1\ddot{\phi} = M_m$.

$$M_m = M_v - I_1 \dddot{\varphi}_1 \tag{5}$$

If I_2 is meaningless in relation to I_1, $M_m \approx M_g$ is... [Remainder of paragraph missing from original document].

If one assumes the known function /38

$$E = E_o + \Sigma E_i \sin \omega_i t \tag{6}$$

as described above, one finds through simple calculations

$$\begin{aligned} M_g &= M_{go} + \Sigma M_{gi} \sin \omega_i t \\ M_m &= M_{mo} + \Sigma M_{mi} \sin (\omega_i t + \alpha_m) \\ M_v &= M_{vo} + \Sigma M_{vi} \sin (\omega_i t + \alpha_v) \end{aligned} \tag{7}$$

Here M_{gi} is directly proportional to E_i, and the relationships M_{mi}/M_{gi} and M_{vi}/M_{gi} are of interest in understanding the mill's influence.

1) If M_{mi}/M_{gi} is substantially larger than 1 for certain frequency domains, there is the danger that certain portions of the

mill directly inside the propeller mounting will be overstressed, even though the output does not go over 200 kW. The result is that those elements of the mill which are not separated from the generator by large rotating masses receive an influence that is always proportional to the output.

2) If M_v/M_g in an area around a certain frequency is small in comparison to I, it results in a resonance phenomenon in that the changes in the wind's drive moment M_v will become greatly enlarged in the neighborhood of ω_r. E will then have a tendency to pulse at a frequency ω_r, but this does not result in a risk for the mill or its sails when it is only $E_{max} \leq 200$ kW.

The following orienting calculations are now performed under the following conditions.

I_2 is determined to be small in relation to the propeller's mass inertia moment I_1.

In the following it is stated that:

$$I_2 = \tau I_1 \tag{8}$$

where τ is small in relation to I. The "placement" of the mass inertia moment I_2 can be varied by setting

$$\frac{1}{k_1} = \frac{1-m}{k} ; \frac{1}{k_2} = \frac{m}{k} \tag{9}$$

where k becomes a kind of spring constant for all the axles in the mill, and where the value 1 of the parameter m results in I_2 becoming essentially disconnected from I_1, and the value 0 of m results in I_2 ... [Remainder of paragraph missing from original]

From the drawings of the propeller, one can calculate $I_1 \approx 30$ tm sec^2, in that for the time being one considers the sails to be infinitely stiff (corrections for this will be discussed later). /39

In the research done at the site, one estimates that the oscillation period for the mill with the generator locked is about 1.5 sec, which gives an equation for the above-mentioned spring constant k.

The damping c_3 can be determined by means of equation (4).

$$M_g = c_3 (\dot{\varphi}_3 - \dot{\varphi}_o) = \frac{0.102\ E}{\dot{\varphi}_o}$$

Since the slip is s%, it follows that $E = E_{max} = 200$ kW and

$$\dot{\varphi}_3 = \dot{\varphi}_o \left(1 + \frac{s}{100}\right)$$

Since $\dot{\phi}_0 = 30$ rpm $= (30 \cdot 2\pi)/60 = 3.14$ rad/sec, one finds that

$$c_3 = \frac{0{,}102 \cdot 200}{3{,}14^2 \cdot \frac{s}{100}} = \frac{206}{s} \text{ tm sec/radian}$$

If one now makes $\tau = 0$, one obtains

$$\frac{M_{vi}}{M_{gi}} = \sqrt{\left(1 - \frac{\omega_i^2\ I_1}{k}\right)^2 + \left(\frac{\omega_i\ I_1}{c_3}\right)^2} \qquad M_{mi} = M_{gi}$$

In Fig. 12, $T = 2\tau/\omega_i$ is set as the abscissa and M_{gi}/M_{vi} is set as the ordinate for various values of s.

This shows that when s = 0.5%, there is a distinct resonance for T ≈ 1.5 sec, and that there is no resonance for s = 2.37%.

When s = 1.1%, as is the case at the Gedser mill, there are only signs of resonance in that it must be stated that the above-mentioned numerical values for the mill's mechanical constants are encumbered with substantial uncertainty, so that the curve for s = 1.1% can in reality lie both higher and lower than shown.

The maximum value is similar to:

$$\frac{1}{\frac{kI_1}{c_3^2}\left(1 - \frac{kI_1}{c_3^2}\right)} \quad \text{when} \quad \omega_i^2 = \frac{k}{I_1} - \frac{k^2}{2c_3^2}$$

The characteristic pull will decrease with larger oscillations in M_g as will the effect when one increases the slip, although the model is in principle correct.

Since Fig. 11 is calculated with $I_1 \approx 30$ tm sec^2, s = 1.1% or c ≈ 188 tm sec/rad and the oscillation period for the locked generator is 1.5 sec, curves for M_{vi}/M_{gi} and M_{mi}/M_{gi} are drawn in Fig. 13 for various values of /40

$$I_2/I_1 = \tau \text{ and } k_1/k_2 = m/(m - 1)$$

in the neighborhood of T = 1.5 sec.

This shows that a mass inertia moment of I_2, similar to 0.2 I_1, placed on an arbitrary plane in the mill, does not have any substantial influence on the situation.

Up to now the propellers have been regarded as infinitely stiff, with a mass inertia moment of 30 tm sec^2.

In reality, the propeller is made up of three elastic girders secured to an axle, and that moment which they transfer to the axle has so far been set similar to

$$M_m = M_v - I_1 \ddot{\varphi}_1$$

Each girder is in reality influenced by a tangential load q_v t/m from the wind and mass energy $-m(\delta v/\delta t)$, where the tangential strength is:

$$v = \frac{\delta}{\delta t} (x\varphi_1 + w)$$

Here x is the distance from the axle and w is the girders' bending.

The conditions in the sails are hereafter based on the equation:

$$q_v - m \frac{\delta v}{\delta t} = E I \frac{\delta^4 w}{\delta x^4}$$

If one sets m, the mass per m with constant I, and the sails' inertia moment into the equation as constants,

$$q_v = p(t) \frac{x}{\ell}$$

which should be approximately correct according to Mr. Juül (engineer), one finds that, when one sets

$$M_v = 3\ p \int_0^{\ell} \frac{x}{\ell}\ x\ dx = p(t)\,\ell^3$$

$$I_1 = 3 \int_0^{\ell} m\ x^2 dx = m\,\ell^3\ (= 30\ \text{tm sec}^2)$$

the result is:

1) the oscillation period for the sails when the hub is considered to be locked is about 0.56 sec,

2) the curve shown in Fig. 13 for $\tau = 0$ is for all practical purposes unchanged when $T \geq 0.5$ sec, when one considers the oscillation period for the mill with the generator locked to be 1.5 sec. /42

That is, the conditions of the mill are satisfactorily characterized by the given model except for very fast oscillations in the wind moment, which would result in the propellers oscillating in such a manner that difficulties are caused in the sails.

Conclusion

It has been found that at the Gedser mill there are oscillations in the given effect or, in other words, the moment M_g, with which the mill influences the generator. These oscillations occur particularly at a frequency of about 0.7 or at an oscillation period of 1.4 to 1.5 sec (Fig. 14).

The above-mentioned analysis shows that in a model which has the same characteristic qualities as the mill, these oscillations will not be accompanied by particularly dangerous influences from specific parts of the mill, but the influences are primarily proportional to the given momentary effect.

In addition, it has been shown that the amplitude of these oscillations will be significantly lowered if one increases the slip, and this will not have any mechanically disadvantageous secondary effect.

The oscillations in the wind's drive moment must be multiplied by a certain factor f in order to convert to the oscillations at the moment when the mill influences the generator, where f is dependent on the oscillation period as shown in Figs. 12 and 13.

These figures are based on information which, in part, is not exhaustive and, in part, is encumbered by substantial uncertainty, so that it would be difficult to draw broad qualitative conclusions from them.

It seems however that the oscillations in the given effect must not have, as a cause, immaterial oscillations in the wind's drive moment. A more exact answer to this can only be obtained by setting up a calculation for an oscillating system which, as much as possible, resembles the mill in all substantial details, or by eventually setting up an examination of actual accessible information from other mills.

1.5.2. Measurements of the Pulsations

The measurements were carried out by SEAS at the Gedser mill by means of a registering ammeter with rapid responses on paper with time markings corresponding to each revolution of the mill's sails. The ammeter was attached to the generator cables /42
through a 400/5 A current transformer.

The following numbers of impulses per revolution were made on recording paper #1-7, on which #1-5 were taken on 6/30/1961 at a wind velocity of 10-15 m/sec, #6 was taken on 7/24/1961 at a wind velocity of 9-10 m/sec (NW), and #7 was taken on 10/17/1961 at a wind velocity of 13-17 m/sec (SW-W).

Curve No. 1		Mill's direction	Impulses	Revolution	imp./rev.
Section	a	Wind direction	155	100	1.55
–	b	–	77.5	50	1.55
–	c	–	42	27	1.55
–	d	–	60	38.5	1.56
Curve No. 2					
Section	a	–	100	64.5	1.55
–	b	–	51	33	1.55
–	c	–	155	100	1.55
–	d	–	63.5	41	1.55
Curve No. 3					
Section	a	–	155	100	1.55
–	b	–	77.5	50	1.55
–	c	–	77	50	1.54
Curve No. 4					
Section	a	–	48	30.9	1.55
–	b	–	155	100	1.55
–	c	Side wind	60	39	1.54
–	d	Rising sail	60	38.6	1.55

Curve No. 1	Mill's direction	Impulses	Revolution	imp./rev.
Curve No. 5				
Section a	Side wind Descending sail	30	19.5	1.54
- b		30	19.5	1.54
- c		28	18	1.55
- d		88	57.2	1.54
Curve No. 6				
Section I	10° left	130	83.7	1.55
- II	10° right	150	97	1.55
- III	10° left	90	58	1.55
- IV	Wind direction	90	58	1.55
- V	10° right	90	58	1.55
- VI	Wind direction	100	65	1.54
Curve No. 7				
Section I	Wind direction	155	100	1.55
- II	-	155	100	1.55
- III	-	155	100	1.55
- IV	-	155	100	1.55
- V	-	155	100	1.55

1.5.3. Experience Regarding the Construction, Etc. /43

Stiffening Girders Between the Sails

In September 1957, there was a break in two of the stiffening girders which are mounted between the sails. With the kind assistance of the Laboratory for the Study of Metal at Denmark Technical University, this problem was thought to be due to metal fatigue. Prof. B.J. Rambøll carried out the calculations for new girders, which were made ready for mounting. Since then, there has been no similar problem.

Sail's Braking Flaps

The mill's braking flaps are moved by three oil pressure-controlled servomotors which are placed on the sails. This system has not worked satisfactorily because the three braking flaps are not mechanically connected to each other, and therefore they do not work at the same time nor together. The oil is led through the mill's axle shaft over a packing brush and a rotating pipe system to each of the servomotors.

With the eventual future building of mills, one should undoubtedly choose the system used at SEAS' Bogø mill. The braking flaps at Bogø are moved by pulling arms that are built into the sails. The pulling arms are connected by a strong coil spring that tightens by means of an electrically driven toothed gear system.

The Machine Housing

The machine housing, together with the sails, has shown a tendency towards rocking. The machine housing turns very easily on two rows of ball bearings, and, with the wind's varying influence on the sails, the machine housing begins to rock to the degree that the wobble in the yaw mechanism's toothed gear allows it.

This could probably be counteracted by having the machine housing turn on a sliding surface.

The construction of the yaw mechanism has shown itself to have various disadvantages in that, since it is so tightly built, it becomes very difficult to repair. Certain parts can only be replaced after the wings and the machine housing have been taken apart.

In July 1960, damage occurred in the yaw mechanism. It turned out that two bolts were broken, probably because they were not sufficiently tightened. After changing to sturdier bolts, the yaw mechanism has worked satisfactorily.

In order that the greatest possible operational safety can be realized, it would be advantageous, particularly in the machine housing, to secure all the connections requiring screws in the relays, machines and apparatuses, so that they do not loosen.

Examination of the sails and the exterior parts of the mill is /44
made difficult by the limited space. This could be improved by making the roof of the machine housing accessible.

Lubrication System

The chains between the propeller shaft and the generator shaft are enclosed in casings. In the beginning, lubrication of the chains took place in oil baths, which resulted in certain disadvantages. In the first place, the oil bath hindered the mill from starting, when the mill, due to lack of wind, had been stopped so long that the oil was cold. Secondly, it was difficult to get the chain casings sufficiently oil-tight, because of the strong oil spraying in the chain casings that gave rise to the atomization of the oil, so that the oil seeped out between the joints as oil vapor.

Lubrication of the chains was therefore changed to pumped lubrication by means of a small electrically driven oil pump which put pressure on the lubrication system, so that the oil was sprayed in on the chains. In this lubrication system, a pressure relay was put in which disconnected the steering connection for the mill, so that the mill stopped if the oil pressure dropped. After the changes in the lubrication system, the gears have functioned without any trouble.

However, it has continued to be difficult to keep the chain casings oil-tight. Spilled oil from the mill is carried some distance away from the mill by the wind and has caused crop damage. In addition, spilled oil is a danger for the maintenance personnel.

By placing spill trays under the chain casings, this difficulty can be overcome.

Electrical Installation

Spilled oil from the machine housing penetrates the electrical cables, and this has made it necessary to change many of the cables. The use of plastic-coated cables is recommended.

Supervision

SEAS has been in charge of the operation of the Gedser mill. Monthly inspections have taken place. In addition, a neighboring farmer has agreed to keep an eye on the mill and report if he observes anything unusual.

This supervision has proved to be satisfactory in connection with the mill's comprehensive safety system, which has worked very effectively.

Enclosure 2. Measuring Wind Effects at the Gedser Mill /45

2.1. Calibration of the Graduated Cylinder

Professor A. Efsen, Doctor of Technology, and V. Askegaard, civil engineer.

The Laboratory for Construction Technology has, for the Wind Power Committee, mounted strain gauges on the graduated cylinders of the windmills, in order to measure the wind effects upon the mill. Furthermore, the graduated cylinder is calibrated for various power effects.

A section through the graduated cylinder is seen in Fig. 15, where the power influences which control the dimensioning of the tower are given, transferred to the measuring cross section.

The foundation of the measuring cylinder was constructed as is shown in Fig. 17, after the method shown in Fig. 16, which used wooden wedges and tension cleats, was found to be unsuitable. The cylinder was sunk down vertically into a layer of soft mortar 3 cm thick, which had been leveled beforehand, so that the container was held in contact with the entire surface of support by its own weight. The mortar layer was spread on the laboratory's stress plane in an area where we had previously repaired fissures and holes. It can be assumed that the compression of the underlayer is very small in relation to the compression of the measuring cylinder.

The measuring cylinder is influenced as shown in Figs. 17, 18, and 19, and as shown in Fig. 22 A,B,C, and D. The placement of the strain gauges is also given in the latter figure. These are placed on the inner side of the cylinder with an angle of 45° between their longitudinal direction and the cylinder's generators, so that two consecutive strain gauges stand perpendicular to one another. In the introductory testing we used strain gauges in positions 1, 2, 17, 18, 33, 34, 49, and 50. For the final calibration, we used all of the strain gauges, 64. The strain gauges are of the type: Gustafsson B 225 S (R = 120 Ω), k = = 2.20, $\alpha = 2{:}10^{-6}\ \varepsilon/°C$). The strain gauges are affixed with heat-hardening L glue, which has been allowed to harden for approximately 5 hours at 120° (see Figs. 20 and 21).

The unit extensions for all of the strain gauges are read /46
off for each of the power influences shown. These readings are then placed in the following measurement expression, which will, in due course, be registered by the measuring instruments.

$$\sqrt{(\varepsilon_n - \varepsilon_{n+1} - \varepsilon_{n+32} + \varepsilon_{n+33})^2 + (\varepsilon_{n+16} - \varepsilon_{n+17} - \varepsilon_{n+48} + \varepsilon_{n+49})^2}$$

$n = 1, 3, 5, 7, 9, 11, 13, 15$ (horizontal power P_x)

$$\tfrac{1}{2}(\varepsilon_n - \varepsilon_{n+1} - \varepsilon_{n+32} - \varepsilon_{n+33} + \varepsilon_{n+16} - \varepsilon_{n+17} + \varepsilon_{n+48} - \varepsilon_{n+49})$$

$n = 1, 3, 5, 7, 9, 11, 13, 15$ (torsional moment M_v)

$$\varepsilon_n + \varepsilon_{n+1} - \varepsilon_{n+32} - \varepsilon_{n+33}$$

$n = 1, 3, 5 \ldots\ldots\ldots\ldots\ldots\ldots\ldots 31$ (overturning moment M_x and M_y)

The value of the uppermost expression is proportional to the value of the horizontal power and should, if the cylinder behaves in an ideal manner, be zero for all of the other power effects. This is correspondingly true for expressions M_v and $M_{x,y}$.

During the introductory testing, where strain gauges were placed in the positions 1, 2, 17, 18, 33, 34, 49 and 50 only it was shown that the above measuring combinations were not completely independent of the extraneous power effects. This is presumably due to the fact that the cylinder in the area next to the weld in the generator direction exhibited definite local denting. Nevertheless, the interim testing showed that there was reason to assume that, if one were to employ a sufficiently large number of strain gauges along the measuring section, one would find strain gauge combinations with which P_x and M_v could be determined with sufficient accuracy.

We therefore employed the 64 strain gauges previously mentioned on the cylinder, and the calibration was carried out as is shown in Fig. 22. On the basis of the measurement results we have made an estimate as to the dependency of the various strain gauge combinations upon the extraneous power effects, so that the most suitable combinations can be chosen and used.

All of the measured values for ε are shown in Fig. 24. In Fig. 25 these values are combined in the above expressions for the measurement of P_x, M_v, and M_{xy}, corresponding to the load instances in Fig. 23. These load instances (B, C, and D) are arrived at on the basis of the corresponding load instances in Fig. 22, by subtraction of the effects of the central normal power. /47 The central normal power has been necessary during the calibration in order that we might be certain that the entire diameter of the cylinder has been in contact with the underlayer at all times.

In Figs. 26 and 27 we have made a calculation of the degree of uncertainty involved in the calculation of P_x, M_v, and M_{xy}.

Fig. 26 gives the degree of uncertainty when P_x = 15,000 kg, and the above power effects are as shown in Fig. 15. Fig. 27 gives the degree of uncertainty when P_x = 7500 kg, and the above power effects are as given in the diagram. In this P_x integral, which is expected to be of the greatest interest, M_x can be assumed to be constant, according to statements from engineer Juul, SEAS.

Commentary, which explains the method used for the determination of the degree of uncertainty, is found with the diagrams.

The following measurement combinations have been chosen as being specially desirable:

1. for measurement of P_x

combination n = 9: standard deviation is 9% when P_x = 15,000 kg
and 23% when P_x = 7500 kg.

combination n = 13: standard deviation is 9% when P_x = 15,000 kg
and 22% when P_x = 7500 kg.

2. for measurement of M_v

combination n = 11: standard deviation is 12% when P_x = (15,000 kg (+ M_v = (_ 5000 kgm
and 16% when P_x = (7500 kg (+ M_v = (_ 2500 kgm

combination n = 15: standard deviation is 10% when P_x = (15,000 kg (+ M_v = (_ 5000 kgm
and 14% when P_x = (7500 kg (+ (_ 2500 kgm

The stated uncertainties in the determination of M_v are correct under the following assumptions: a) M_v fluctuates around a zero position which is determined in that P_x attacks the propeller shaft, b) the windmill's yaw and the variation of M_x are very slow in relationship to the variation of M_v.

The determination of M_y is encumbered in that the point of attack for P_x is determined with a degree of uncertainty of approximately 5 cm in the z axis' direction, when P_x attacks in the direction X or I (see Fig. 22C). When P_x attacks in other directions, the degree of uncertainty is approximately 20 cm.

The theoretical and measured relationship between the above expressions for P_x and M_v, expressed by ε and the amount of power influence, is shown in Fig. 28. There is excellent agreement between the theoretical and measured curves, which are straight lines. Since the unit extensions in the measuring cylinder are very small for the given effects, it will be natural to assume that the proportion will be valid also for values of P_x and M_v which are considerably larger. /48

2.2. Postcalibration and Measurements

Professor A. Efsen, Doctor of Technology, and V. Askegaard, civil engineer.

The calibration of the measuring cylinder for the windmill at Gedser was described in Enclosure 2.1. Because of deviations from the cylindrical surface of rotation arrived at during the construction and also because of the small height of the measuring cylinder, which rendered the deformation state in the measuring positions dependent upon the foundation specifications, a greater number of strain gauges was affixed to the cylinder. Combinations of these strain gauges were selected for the measurement of the individual power effects, and from these combinations, the most efficient were selected, during a calibration made in the research laboratory of the Laboratory for Construction Technology. By "an effective combination for the measurement of M_v, for example," we mean a combination which gives a signal which is unambiguously connected with M_v, and therefore independent of the other power effects (for example, P_x, M_x, and M_y). Complete independence of the above power effects was not achieved, for the above-mentioned reasons.

For the placement of the strain gauges, see Fig. 29.

Fig. 30 shows a photograph of the windmill, with the placement of the measuring cylinder indicated.

In the above report, the measurements at Gedser were supposed to be continued over a long period of time, with registration of the horizontal power $P_x = \sqrt{P_A^2 + P_B^2}$, the torsional moment M_v, and the overturning moments M_x and M_y. (The coordinate system is shown in Fig. 29.)

However, the test technique was changed, so that only the two components of P_x and M_v were determined during the measurements at Gedser. Instead, measurements were made on the days which exhibited desirable wind conditions, and here we have drawn up the signals for short periods (approximately 5 sec), during which time the wind speed can be assumed to almost constant.

After the test windmill at Gedser was constructed, calibration of the selected combinations was made, from May 13-15, 1959. The power effect was the overturning moment, which was due /49
to the machine house's eccentrically active net weight M_y = = 12.8 t x 1.14 m = 14.6 tm. In the case of bending of the machine house, this overturning moment can be turned in relation to the measuring cylinder, and from this we can establish a comparison with the corresponding calibrational testing in the test facilities at the Laboratory for Construction Technology. No calibration can be made on the windmill for a horizontal force or a torsion moment. However, the latter effects were shown to entail considerably smaller degrees of uncertainty than the overturning moment, during calibration in the test facilities.

On the basis of the calibration at Gedser, the combinations indicated in Fig. 29 were selected for the measurement of P_x and M_y, because their sensitivity to M_y was on the same order as the sensitivity exhibited in the laboratory testing.

The foundation specifications, or the manner in which the forces are transferred to the measuring cylinder, are not the same in the two cases. In Figs. 31-33 one can see that, in time, a change might be made.

Measurements were taken with the windmill in action on 10/27/1959, with wind speeds of between 12 and 20 m/sec. On 10/29/1959, measurements were made with a still windmill, with wind speeds of 4-5 m/sec. This final measurement forms the foundation for the determination of the measurement combinations reading at 0 m/sec, which is the starting point for the determination of the measured wind forces. The windmill is in the same position as on 10/27/1959.

A corresponding measurement is taken with the windmill in motion, on 11/2/1960. The wind speed here was between 11 and 16 m/sec. Measurements were made with a still windmill in the same position on 11/9/1960. The wind speed here was approximately 6 m/sec. The wind situation during the measurements can be seen in Fig. 34.

As previously mentioned, the film was taken for a few seconds, as the wind speed is almost constant during this interval. The wind speed is measured with an instrument which is connected to a cup anemometer approximately 25 m west of the windmill, and mounted at a height of approximately 10 m. This instrument is mounted with clamps.

The films which were taken are included with the report. Two typical histories are shown in Fig. 35. Zero lines for the individual signals are indicated, and the relationship between amplitude and the unit extension ε is also given, so that additional collaboration of the films can be made, if necessary. The connection between ε and the measured wind forces is shown in the calibration curves in Fig. 36. /50

In the film which was made on 11/2/1960, the sail's position through a swutching arrangement is shown, as it appears in Fig. 35.

The zero lines in Fig. 35 are established after the corrections have been made for the effect of the overturning moment M_y from net weight and P_x, and the overturning moment from the torque moment M_x. The corrections are made on the basis of Figs. 31 through 33.

In the corrections we have ignored the contribution which is due to the fact that it was not wind still during the control measurements on 10/29/1959 and 11/9/1960, when there was 4-5 m/sec and approximately 6 m/sec respectively.

The resistance coefficient for the windmill sails in the case of a windmill at rest can be assumed to correspond to the resistance coefficient for rectangular plates where the relationship 6 between the length and the width, according to Hütte I, Vol. 26, p. 390, is:

$$c = \frac{w}{q \cdot F} = 1.23$$

where c is the resistance coefficient
w is the resistance in kg
F is the sail area $3 \times 9 \times 1.5 \approx 40 \text{ m}^2$
$q = 1/2\ pv^2 \text{ kg/m}^2$
v is the wind speed in m/sec
$p \approx 0.13 \text{ kg} \cdot \text{sec}^2/\text{m}^4$

which gives us $w = 3.2 \cdot v^2$ kg.

The relationship between w and v is indicated in Fig. 37. It follows from here that the correction resulting from the wind speed, which is 5-6 m/sec, has no meaning, both for P_x and M_y. It can be seen in Fig. 35 that the torsion moment fluctuates around the zero line with approximately the same fluctuation to both sides.

The greatest values for P_x and absolute value of M_y for each individual film seen are given in diagrams 1 and 2, on the following pages. Graphs of the results from these diagrams are given in Fig. 37.

The degree of uncertainty of the readings is estimated to be: approximately 700 kg for P_x and approximately 700 kgm for M_y.

Continuing with the above measurements, the measurements made on 1/13/1962 were made with a wind speed of between

19 and 27 m/sec. In addition, measurements were made on 1/15/1962 with a still windmill, where the wind speed was 7-8 m/sec. /51

Time	Film No.	Scene No.	Wind speed m/sec	P_x max kg	$\lvert M_y \rvert$ max kgm
16:50	8	1	12	3500	3300
		2	11	3700	1600
		3	12	3700	1300
16:53		4	12	3500	1800
17:12	9	1	13	3200	1300
		2	12	3300	1600
		3	12	3000	2300
		4	13	3700	2100
		5	12	3700	2300
		6	12	3500	2500
		7	14	3700	2000
		8	12	3300	2500
		9	13	3300	1500
		10	14	3700	2000
17:23	10	1	13	3900	2100
		2	14	4500	2900
		3	13	4200	2700
		4	16	4500	2900
		5	15	4100	2100
		6	14	4100	3300
		7	13	3900	2100
17:26		8	Calibration		

Diagram 1. Measurement on 11/2/1960.

Film 6: calibration on 11/2, time 16:05.
Film 7: two scenes, each of approximately 20 sec duration, wind speed 10-12 m/sec, on 11/2, time 16:30.
Film 11: calibration on 11/9, time 14:25.

Time	Film No.	Scene No.	Wind speed m/sec	P_x max kg	$\lvert M_v \rvert$ max kgm
15:55	2	1	18	4600	1600
		2	16	5300	2300
		3	18	5300	4800
		4	16	5000	1900
		5	18	5500	2500
		6	16	4200	2300
		7	18	5300	2300
		8	17	5900	1600
		9	16	4100	2500
		10	15	4800	2500
16:01		11	17	4400	2500
16:33	3	1	14	4100	1400
		2	12	4600	3300
		3	17	4800	3500
		4	17	4200	4000
		5	15	5000	4000
		6	15	4600	3300
		7	16	6300	4600
		8	13	4100	3100
		9	12	3900	1900
		10	12	3900	2300
17:25	4	1	19	4400	1900
		2	20	5900	3100
		3	19	6300	5900
		4	18	5300	1900
		5	19	4800	1400
		6	19	5000	2500
		7	18	5900	6500

Diagram 2. Measurement on 10/27/1959.

Film 1: calibration on 10/27, time 15:35-15:43
Film 5: calibration on 10/29, time 13:50

Time	Film No.	Scene No.	Wind speed m/sec	P_x max kg	$\|M_v\|$ max kgm
14:00	12	1	27	7200	5800
		2	24	7600	4300
		3	24	6800	4100
		4	23	7000	4700
		5	23	6800	3900
		6	22	7000	4300
14:10		7	24	7200	4500
15:00	13	1	19	6600	3100
		2	19	6100	2000
		3	20	5900	3600
		4	21	5900	3700
15:10		5	21	6100	2100

Diagram 3. Measurement on 1/13/1962.

Film 14: calibration on 1/13/1962.
Film 15: calibration on 1/15/1962.

The results from the last measurement are included in Figs. 31, 32, and 33, which show that the foundation specifications are underoing constant change.

The wind situation is shown in Fig. 34, and diagram 3 above shows the measuring results, after the corrections have been made. Fig. 37 shows a graphic representation of the measured results.

2.3. Expenses for Construction and Measuring (as of March 31, 1962)/53

Measuring cylinder (incl. projection and mounting)		kr. 15,690.00
Diverse changes		kr. 11,845.96
Payment concerning pulsation investigations	kr. 4,700.10	
Measurements from windmill	kr. 25,960.00	kr. 30,660.10
		kr. 58,196,06

Enclosure 3. Wind Measurements

Doctor of Philosophy and Technology Martin Jensen

3.1. Positioning of the Measuring Stations

The Danish stations for measurement of wind conditions are placed at Gedser, Torsminde, and Tune, as is shown on the map in Fig. 38.

The selection of these places is based upon a consideration of the topographical descriptions stated below.

A 25 m high mast, which holds the apparatus, is found at each station. This height was chosen because the hub on the test windmill at Gedser is located at this height.

The effect of the wind increases proportionally with the height above the ground. In order to find out whether it is economically feasible to built higher windmills, in other words, if the greater wind effect can pay for the more costly construction of the windmill, a mast 50 m high was placed at Gedser, in addition to the 25 m high mast already present.

3.1.1. Gedser

The station at Gedser lies 3 km north of Gedser. The test windmill is located here, in addition to the two stations used for measuring wind forces, one apparatus station located 25 m above the ground and the other located 50 m above the ground. Fig. 39 shows their placement.

The test installation lies 300 m from the west coast of Falster. Here, Falster is 3 km wide from east to west. The terrain slopes from the east coast upwards toward the test installation, where the terrain lies 10 m above sea level; from here, the terrain slopes downwards towards the western coast, where the land ends with a cliff 5 m high. The entire area is flat farming land.

As is shown on the map in Fig. 40, the location is exposed to winds in the sector extending across the south, from west to north-northeast, as the wind in these directions is coming across 45 km of open ocean. There are also considerable stretches of water over which wind must pass in the sector across the northwest, from west to north-northwest. The only land winds come from a small sector lying approximately north. [Remainder of paragraph missing from original document]

Since the north wind is the least common in Denmark, the placement of a wind-driven electrical generator at Gedser must be considered nearly optimal with regard to the production of maximum energy. /55

3.1.2. Torsminde

Torsminde is a small village by the sluice which drains into Nissum fjord. It is located in the middle of the small isthmus, running north to south, which separates the North Sea on the west from Nissum fjord on the east.

The measuring station is located south of the village, out towards the ocean, on terrain which lies 2 m above sea level. The measurements are made 25 m above the ground surface.

Torsminde was chosen because here one is free of the high sand dunes, which are otherwise characteristic for the western coast of Jutlands.

The village of Torsminde consists of houses between 3 and 5 m high, and built upon terrain of the same elevation as that upon which the mast stands.

As is shown on the map in Fig. 41, the location is completely exposed to ocean winds in the sector across the west from northwest to southwest.

The location is also quite favorable for the easterly winds coming from the fjord, and, because the land in back is flat, it is open country, at least within a radius of 15 km.

Only in a small sector in the north and a corresponding sector in the south is the wind reduced, when is passes the isthmus. At these points, the isthmus consists of the more characteristic sand dune landscaping.

With respect to the dominant westerly winds present in Denmark, the station at Torsminde must be assumed to represent the optimal placement for the Jutlandish peninsula.

3.1.3. Tune

The station for the measurement of wind at Tune is placed 25 km west of Copenhagen (Fig. 42). The measurements are made 25 m above the ground surface.

The station is built upon a weak elevation in the terrain, running north to south, and lying 62 m above sea level. The terrain east and west of the station slopes downward slightly.

The area is completely open and lightly rolling farm land.

Wind from all directions passes considerably distances over land, except for wind from the southeast.

The station at Tune is representative of the best possible situation of a station in Denmark, if the station is to be built inland.

3.2. The Stations for Wind Measurements /56

3.2.1. Mast and Hut

The sensing elements of the measuring apparatus are mounted on the top of a pylon. It is a lattice work, triangular in cross section, and all of the poles are of round steel. A small balcony is placed at the top of the mast, for inspection of the apparatus. The measurement readings are made in a hut at the foot of the tower (Fig. 43).

3.2.2. Effect Distribution Measurements

The test windmill at Gedser operates on the following principle: the propeller drives an asynchronous generator by means of a constant gear, which is linked to an electrical network, whose frequency is determined by the main steam power plants which are connected to the network.

This construction means that the sails' rpm fluctuates approximately 1% between no-load operation and full-load operation. The blades themselves cannot be adjusted. It must be noted that the rotatable blades alone serve as a brake in stopping the working system.

The efficiency of such a wind-driven power plant has a maximum value for a determined wind speed, which depends upon the degree of gearing between the generator and the sails. If the wind speed increases beyond this point, then the wind's attack angle to the blades will become too great, and the result will be that the effectiveness of the windmill is decreased. The blades will stall in the case of even greater wind speeds, and the effectiveness is greatly decreased.

When constructing a windmill according to this principle, one must recognize the span of wind speeds at which the windmill will function most efficiently. It is therefore extremely necessary to be familiar with the distribution of the wind energy in relation to the various wind speeds.

A new system was constructed for this purpose, a system which could integrate the wind energy distributed according to wind speed, which can be called an effect distribution meter, or Ef-meter. The apparatus integrates the wind discontinually, that is, in the following six areas: 0 to 4 m/sec, 0 to 6.5 m/sec, 0 to 9 m/sec, 0 to 11.5 m/sec, 0 to 14 m/sec and 0 to 16.5 m/sec.

The selection of these particular values occurred on the basis of a careful examination of the existing information concerning Denmark's wind climate. The measurements have substantiated this selection as being particularly suitable to our purposes.

As was previously mentioned, the Gedser windmill's rpm fluctuates only 1% from no-load operation to full-load operation, and it will therefore assume responsibility for gusts of short duration. [Remainder of paragraph missing from original document]

As is the case for most wind-driven power plants, the Gedser windmill rotates slowly into the wind, and it cannot be reponsible for short-term variations in wind direction; the Ef-meter is constructed correspondingly. /57

An Ef-meter has six sensors mounted on a horizontal beam at the top of the mast. This beam is rotated by a machine in such a way that it maintains the same angle of incidence to the wind as the Gedser windmill. Each sensor contains a movable plate which is perpendicular to the wind direction. A spring presses the plates forward against the wind; if the wind speed exceeds the characteristic value of the sensor, then the plate is pressed backwards slightly, tripping a switch in a circuit which includes an electrical counting device.

The measuring method is basically statistical, in that a synchronous system in the hut sends an impulse every 15 sec to all of the sensors, and more or fewer of the counting devices will register a completion of their circuit, according to the wind speed. There is, in addition to the six aforementioned counters, an additional counter which counts all of the impulses sent out.

A detailed description is found in Section 3.3.

3.2.3. Meter for Maximum Speed-Pressure

At each station there is a system for measuring the maximum value of the wind's speed-pressure, q_{max}-meter. These measurements are made in order to obtain a statistical overview of the wind's stagnation pressure, from which one can derive the wind stresses which are to be used for the calculation of not just windmills, but also of constructions in general.

The sensor is a large Pitot tube, which is held up in the wind by a wind vane. Two pipe conduits lead from the sensor down into the hut, where the pressure moves a float vertically. This motion is registered on a cylinder, but the cylinder is not moved, except for a slight rotation at midnight. Thus, this system shows each day's maximum stagnation pressure.

A detailed description is found in Section 3.4.

3.3. Effect Distribution Meter

3.3.1. Sensors

Six sensors, mounted upon a 4-m-long horizontal beam at the top of the mast, are used in this system (Fig. 44). The beam rotates about a vertical axis, so that it is always perpendicular to the wind. The rotational machinery is an electric motor, which is geared to give the beam a full rotation in 15 min, corresponding to the Gedser windmill's time of rotation. [Remainder of paragraph missing from original document]

The sensor is shown in Fig. 45. The plate pl is 15 x 15 cm, p below is the pivotal mounting, H above is the head of the spring s, which pushes forward with a force which is different for each of the six sensors, which together compose a set. /58

When the wind pressure upon the plate exceeds the characteristic value of the sensor, H will be moved backwards, thereby rotating the unit u, so that the switch for the electrical circuit is closed at c.

This is shown in detail in Fig. 46. When the wind pressure increases, H will first move 1 mm, before the finger f is touched. During the next millimeter movement, the switch spring cs is moved forward to the contact switch at c. H afterwards moves another 1 mm before impact, during which time spring cs is bent, since it is quite flexible. In the case of decreasing wind pressure, H first moves 1 mm, and u remains at rest, because of the friction spring ts. During the next millimeter's motion of H, f is also moved, and cs straightens out, so that there is contact at all times. Only when H has moved more than 2 mm is the contact with c broken. H now moves its third millimeter forward to the impact point f, leaving a 1 mm gap at c.

This arrangement is used in order to hinder circuit completions in rapid succession which are due to the turbulence of a wind whose pressure upon the plate corresponds exactly with spring s of the sensor in question.

The plate pl consists of 0.4 mm aluminum plate in a framework of duralumin. The spring s is made of phosphor bronze.

Contact c is equipped with contact surfaces of platinum. The rest of the apparatus is made of brass. The apparatus box is shown open in Fig. 45. In operation this box is locked with a deck plate.

The six sensors, which make up a set, indicate circuit completion when the wind speed exceeds the following values:

Sensor No. 1	4.0 m/sec
" " 2	6.5 m/sec
" " 3	9.0 m/sec
" " 4	11,5 m/sec
" " 5	14.0 m/sec
" " 6	16.5 m/sec

The sensors are adjusted in the wind laboratory's 60 x 60 cm wind tunnel. The adjustment is repeated after approximately 1 year. Variations in the apparatus have been minimal. /59

3.3.2. Friction Contacts

Cables lead from the sensor's binding screws to a system of friction rings, which are mounted upon a stanchion located at the beam's midpoint (Fig. 47). At this point the beam's rotations are overcome, so that a fixed cable can continue upwards, over to the stanchion for q_{max}-meters and down to the hut (see Fig. 44).

The friction rings and the clamping shoe are made of hard-chromed brass.

3.3.3. Pulse Generator

A pulse generator in the hut sends a 15 sec current to all of the sensors. In Fig. 48 this pulse generator is a self-starting synchronous motor, which, by means of a gear, rotates the arm once every 15 sec. The head h of the microswitch m is pressed in after each revolution, releasing the battery's 27 V to all of the sensors.

3.3.4. Recording

Each sensor is connected to an electric counting device, as shown in Fig. 48. Counter No. 0 has no sensor, but instead counts all of the impulses sent out by the pulse generator. Counter No. 1 will tally whenever the wind speed is above 4.0 m/sec, counter No. 2 tallies whenever the wind speed is 6.5 m/sec and above, and so on.

The counters are five digital computers of 24 V, the resistance is 500 ohms.

3.3.5. Theory

We will use the following designations:

i is the impulse time, in other words, that interval, during which the head h holds m in.

t is the impulse distance, in other words, the interval from the beginning of one impulse to the beginning of the next.

r is the counter's reaction time, in other words, the interval when current shall flow to a counter, resulting in one tally. /60

c is the switch time, in other words, the interval when the sensor switch is closed.

In Fig. 49 the time runs towards the right (x). A contact in the sensor such as c1 will not register a tally, but c2 and c4 will register a tally, whereas c5 will not register a tally. In other words, tallies are registered from $x = r$ to $x = 1 + c - r$, that is, in the interval $i + c - r - r = 1 + c - 2r$. The interval which registers a tally $i + c - 2r$ must be equal to c, that is, $i = 2r$.

When $i = 2r$, two tallies cannot occur during one impulse.

We shall now consider how the accuracy demand $1 = 2r$ shall be satisfied.

The apparatus should tally c/t, but it actually registers $(i + c - 2r)/t$. The error is $(c/t) - [(i + C - 2r)/t] = (2r - 1)/t$. If we set $i = \alpha 2r$, then the error of the apparatus becomes $(2r - 1)/t = (2r/t)(1 - \alpha)$. r is approximately 0.035, $t = 15$ sec, so the error is $(2 \cdot 0.035/15)(1 - \alpha) = 0.005(1 - \alpha)$. Since α in our system lies between 0.7 and 1.4, the maximum error is 0.002.

3.4. Measurement of Maximum Stagnation Pressure

3.4.1. Sensors

The sensor is shown in Fig. 50. The upper portion, with the head h, the wind vane wv, and the cylinder c, is rotatable. The wind vane makes sure that the head h is always in the wind. There is a 25 mm boring in the head, where the total pressure is measured, that is, the sum of the stagnation pressure and the static pressure. This pressure is conducted through a 25 mm pipe through the apparatus to outlet t1.

The cylinder c has slits in the two generators, where the pressure is exactly zero. Therefore, the static pressure is found in the cylinder, and this pressure is conducted to outlet t2.

Rubber hoses lead from t1 and t2 over to the middle of the mast, where there is a pipe connection down to the hut. These pipes are 3/4 in. in the 25 mm masts, and 1 in. in the 50 mm mast. [Remainder of paragraph missing from original document]

3.4.2. The Recorder /61

The two pipes in the hut lead to the connecting pipes on a water tank, as shown in Fig. 51.

The float f1 is influenced from below by the wind's pressure plus the static pressure; the float is influenced from above by the static pressure. The resulting force is therefore the wind's stagnation pressure, so that the height of the float is an indication of the stagnation pressure.

The cylinder t is shown in Fig. 52. It is a piece of smooth brass piping, whose surface has been carbonized. u is a self-starting synchronous motor with a gear whose axle rotates once per 24 hours. By means of a ratchet mechanism, the synchronous motor causes the cylinder to rotate 3 mm forward every day, at 0000 GMT.

A vertical line is therefore drawn upon the cylinder every day, and the top of this line indicates that day's maximum stagnation pressure. There is room on the cylinder for 50 day's registration; when the cylinder is full it is fixed by immersion in cellulose varnish.

The system is adjusted each time the cylinder is changed, with the help of a Fuess manometer.

The system is set up to register a maximum stagnation pressure of 156 kg/m^2, which corresponds to a wind speed of 50 m/sec.

When the stagnation pressure is under 4 kg/m^2, the sensitivity of the apparatus is very poor, but this is naturally meaningless in that the point of the apparatus is to measure the large stagnation pressures. Fig. 53 shows an adjustment curve.

3.5. The Wind's Effect Distribution

3.5.1. Theory

The wind speed is in a state of constant flux. There are short pulsations corresponding to the turbulence, and variations lasting anywhere from a fraction of a second up to several seconds. Greater pulsations in the wind, with a duration of several minutes, are called squalls. Finally, there are the variations in the wind speed which correspond to the passage of low pressure fronts; in this case the time intervals are hours and days.

Over a longer time period, the wind speed's chronological distribution can be illustrated as shown in the upper portion of Fig. 54. The abscissa is the wind speed v; the ordinate is the accumulated frequency H. H is dimensionless. The corresponding /62 ordinate H_1, up to a certain speed v_1, indicates the time when the wind speed has been greater than v_1, in relation to the length of the interval in question. The curve's ordinate for $v = 0$ is therefore 1, and the curve intersects the abscissa axis at the greatest wind speed which occurred in the interval under consideration.

If this curve is differentiated once, and the signs are changed, then the frequency distribution is derived from the wind speeds, as shown at the bottom of Fig. 54. The abscissa is the wind speed, and the ordinate is the frequency h of the wind speed in question. The ordinate's dimensions are reciprocal to a speed. Only the wind speed v_1 has a frequency h_1.

The relationship between the two curves in Fig. 54 is perhaps most easily perceived by the recognition that the area outside of v_1 in the lowest curve is equal to the ordinate of v_1 in the upper curve. The area under the lowest curve is dimensionless; the entire area under the curve is I.

The effect E of a wind with speed v, is the product of the speed-pressure and the speed.

$$E(v) = 1/2\ \rho\ v^2 \cdot v$$

v is the wind speed in m/sec
ρ is the air's density in $(kg/m^3)(sec^2/m)$
E assumes the dimensions $(kg/m^3)(sec^2/m)(m^2/sec^2)(m/sec) =$
$= (kg/m^2)(m/sec)$ kpm/sec $= 9.81$ W.
kg, here and in the following, refers to kilograms force.

One can, on the basis of the lower curve in Fig. 54, determine the wind's effect distribution by multiplying the ordinates with the effects corresponding to the abscissa; the curve is shown in Fig. 55. The abscissa is the wind speed. The ordinate is the corresponding energy.

$$e_1 = h_1 \cdot \frac{I}{2} \rho v_1^2 \cdot v_1 \text{ with the dimensions } \frac{sec}{m} \frac{kg}{m^2} \frac{m}{sec} = \frac{kg}{m^2}$$

The area under the curve in Fig. 54 is the wind's average effect over the interval under consideration, with the dimensions $(kg/m^2)(m/sec)$.

3.5.2. Collaboration of the Measurements

The method used for collaboration of the readings from the Ef-meter is most easily explained by an example.

The following measurements were made at the station in Tune, in the interval between December 24, 1959 and February 11, 1960: /63

Counter No.	Tallies	Relative	Wind speed greater than
0	283 689	1.000	0 m/sec
1	240 649	0.850	4.0 "
2	134 342	0.475	6.5 "
3	64 665	0.228	9.0 "
4	26 617	0.094	11.5 "
5	7 658	0.027	14.0 "
6	1 398	0.005	16.5 "

Counter 0 has counted all of the impulses, counter 1 has counted the impulses whenever the wind speed was greater than 4.0 m/sec. As can be seen in the table, this was the case 85% of the entire time.

Using the relative values noted in the table as the ordinate, and the wind speed as the abscissa, the curve shown in Fig. 56 is achieved, which indicates the accumulated frequency.

This curve is differentiated graphically, and by this means the distribution in time of the wind speed is derived, Fig. 57. The ordinate is sec/m, the abscissa is the wind speed in m/sec. The area under this curve is 1.

From the distribution of wind speed in Fig. 57 the curve for effect distribution can be calculated, as is shown in Fig. 58. The ordinate is kg/m^2, and the abscissa is the wind speed in m/sec. For $v = 7$ m/sec, Fig. 57 gives an ordinate of 0.12 sec/m, the speed-pressure for this wind speed is $a = 1/16 \cdot 7^2 =$ $= 3.06$ kg/m^2, and the wind's effect $qv = 3.06 \cdot 7 = 21.42$ (kg/m^2)(m/ /sec). The ordinate in the curve for the effect distribution therefore becomes $0.12 \cdot 21.42 = 2.57$, and the dimensions become (kg/m^2)(m/sec)(sec/m) = kg/m^2.

The area under the curve in Fig. 57 is the average effect over the interval in question, which is 33.2, and the dimensions are (kg/m^2)(m/sec).

3.5.3. Results

The measuring stations were started at the end of 1957, and there follows, with some discontinuations, the results up until the end of December 1961. The stations operated without discontinuation from the end of 1959 on.

The results of the measurements made in 1960 are given in the table [following page]. The effect is the average value of the period in question, in (kg/m^2)(m/sec). /64

The distribution of the effect according to the wind speeds for the year 1960 is shown in Fig. 59.

The effects found in 1961 are shown in the table [p. 56]. The measurements were concluded on December 21 and 26, 1961; we have indicated measurements from 1960 to fill in the rest of the days of the year.

The effect is the average value for the period in question, in (kg/m^2)(m/sec).

As was previously mentioned, the measurements have been made throughout a 4 year period, with some discontinuations. The results are not completely evenly distributed throughout the year, in that the winter months are covered by 3 or 4 years' measurements, while the summer is only covered by 2 years' measurement. /65

In Fig. 60, the averages of all of the measurements are shown. The abscissa is the course of the year, and the ordinate is the average effect in (kg/m^2)(m/sec).

Taking all of the measurements into consideration, the probable yearly average effect equals:

Tune		Torsminde		Gedser	25 m	50 m
Date	Average effect.	Date	Average effect	Date	Average effect	Average effect
1960		1960		1960		
1/1	33.2	1/1	69.8	1/1	48.4	61,2
2/11	21.4	1/25	48.2	1/12	51.6	69.4
4/2	35.3	2/20	41.5	2/18	49.7	60.0
5/14	19.9	4/2	53.6	4/2	45.7	52.7
3/7	15.8	5/14	38.2	5/14	39.6	40.6
8/18	18.0	7/2	28.0	5/2	24.8	30,1
9/19	21.1	8/13	29.1	8/13	32.2	40.1
10/22	34.1	9/17	28.1	9/17	28.8	36.7
12/3	26.8	10/22	53.0	10/22	51.3	64,4
12/31		12/3	45.4	12/3	56.1	62,2
		12/31		12/31		
1960	25.2	1960	42.0	1960	41.8	50.8

Tune	29 $\frac{\text{kg force}}{m^2}$	=	285 W/m^2
Torsminde	49 "	=	480 "
Gedser 25 "	42 "	=	410 "

The relation between the effect at 50 m and at 25 m in Gedser is, on the average, 1.21.

3.6. Maximum Stagnation Pressure

/66

The measurements of the daily maximum stagnation pressure were started at the end of 1957 at all four stations, and were made with a few discontinuations.

Tune		Torsminde		Gedser 25 m	
Date	Average effect	Date	Average effect	Date	Average effect
1961		1961		1961	
1/1		1/1		1/1	
	26.8		45.4		56.1
1/7		1/7		1/7	
	30.3		45.4		45.8
2/11		2/11		2/11	
	23.1		30.4		26.7
3/11		3/9		3/8	
	59.0		53.7		58.8
5/6		5/1		5/6	
	21.8		46.6		34.2
7/15		7/15		7/16	
	21.2		42.7		24.0
9/16		9/17		9/9	
	20.5		53.6		33.8
11/10		11/2		10/29	
	30.8		63.3		61.2
12/21		12/26		12/26	
	26.8		45.4		56.1
12/31		12/31		12/31	
1961	29.4	1961	49.0	1961	42.3

A temporary collaboration of the results up until the summer of 1961 is published in Ingeniøren (23) (Dec. 1, 1961); but the measurements must be continued for a few more years in order to obtain a sufficient amount of data for the final statistical collaboration, which will result in a determination of the maximum values for a more closely determined number of years.

The greatest values measured at the four stations, up to the summer of 1961, are:

Tune (25 m), 2/21/1959 q_{max} = 51 kg/m^2 (v_{max} = 28.5 m/sec)
Gedser (25 m), 1/19/1958 q_{max} = 73 kg/m^2 (v_{max} = 34 m/sec)
Gedser (25 m), 1/19/1958 q_{max} = 81 kg/m^2 (v_{max} = 36 m/sec)
Torsminde (25 m), 2/6/1961 q_{max} = 86 kg/m^2 (v_{max} = 37 m/sec)

In addition, we can state that, at Gedser, the relationship between the stagnation pressure at 50 m and at 25 m is 1.13. This relationship in effect was 1,20, which agrees with the results of the direct measurements.

3.7. Expenses for Construction and Measurements (as of March 31, 1962)

Steel masts	kr. 42,614.00	
Effect distribution meters, anemometers	" 7 308.75	
Yaw apparatus, measuring arrangements	" 22,505.25	
Housing for wing measuring instruments	" 5 844.77	
Miscellaneous	17,930.00	kr. 96,201.86
Planning		" 34,729.37
	Total construction costs	kr. 130,931.25
Salaries		kr. 19,616.45
	Total	kr. 150,547.68

Enclosure 4. Considerations Concerning the Competitive Power of Wind-Generated Electricity as Opposed to Steam-Generated Electricity

Director, P. Poulsen-Hansen, civil engineer

4.0.1. Construction Costs

1.1. Per kW machine power for wind power plant A kr.

1.2. Per kW machine power for steam power plant B kr.

We are assuming 6% per year, and a depreciation period of 25 years for both types of construction, corresponding to the expected physical lifetime, yearly payment 7.82%.

4.0.2. Utilization Time of Rated Output

2.1. Wind power: The yearly production in kWh per kW machine power is called E, which is therefore the utilization time of the rated output.

2.2. Steam power: According to our previous experience with the large Danish power works, the utilization time for the year's maximum load is approximately 4000 hours (4000 kWh produced per kW maximum load). In the future, as the large cooperative cables for 120 and 150 kV are developed, the power plant groups will be able to be satisfied with a very modest reserve, so that the total rated output needs to be only 25% greater than the year's maximum load, which means that, in the case of steam power, the utilization time for the rated output will be 4000:1.25 hours = 3.200 hours.

4.0.3. Capital Costs per Produced Net kWh from Plant

3.1. Wind power:

$$\frac{A \times 0.0782 \times 100}{E} \text{ øre/kWh} = 7.82 \times \frac{A}{E} = 7.82\,\alpha \text{ øre/kWh}$$

in that $\alpha = A/E$ expresses a wind power plant's construction costs in kr/kWh yearly production.

3.2. Steam power:

$$\frac{B \times 0.0782}{3200} \times 100 \text{ øre/kWh} = 10^{-3} \times 2.44 \times B \text{ øre/kWh net}$$

4.0.4. Operational Expenditures per Produced Net kWh from Plant /68

4.1. Wind power: a øre per kWh

4.2. Steam power: b øre per kWh

a: There are no fuel expenditures in the case of wind power, but rather expenditures for lubrication, maintenance, and inspection. According to our experiences with the Gedser test windmill, we can say that a will be less than 1 øre per kWh.

b: Operational expenditures are the total of expenditures for fuel and for repairs and maintenance. The fuel expenditure is a product of the specific use q kcal/kWh net, and the fuel price C kr/Gcal, so that the fuel expenditure equals $10^{-4} \times q \times C$ øre/kWh. According to "Danish Electrical Plant Statistics" and from information procured from the larger electrical plants, the other portion of the operational expenditures is derived -- for a utilization period of 4000 hours at maximum -- 0.75 øre/kWh net, and we therefore get:

$$b = (10^{-4} \times q \times C + 0.75) \text{ øre/kWh net.}$$

4.0.5. Cost Price per kWh from Plant

5.1. Wind power: $7.82\alpha + 1$ øre/kWh

5.2. Steam power: $10^{-3} \times 2.44 \times B + 10^{-4} \times q \times C +$ 0.75 øre/kWh. The following values can be calculated on the basis of the present construction costs for steam power plant construction, and on the basis of their fuel costs:

$B = 800$ kr/kW steam power plant

New steam power plants have a specific fuel use of

$q_n = 2500$ kcal/kWh

and the large power works' yearly average (1959/60) was

$q_g = 3100$ kcal/kWh

Setting in these values, the cost will be:

5.2.1. New plants: $2.7 + 0.25$ C øre/kWh

5.2.2. Average existing plant: $2.7 + 0.31$ C øre/kWh

4.0.6. Probable sum of Capital and Operational Expenditures Together with the Cost of the Electricity's Transmission

In this case, the wind power plants are assumed to be evenly distributed throughout the land, and coupled to the existing 10 kV transmission net. The individual electrical distribution consumers have a comparatively limited geographical extent, and they must therefore anticipate complete calm in the entire supply area. [Remainder of paragraph missing from original document]

If an electrical consumer, who normally buys output and energy /69
from a large power plant builds a wind power plant for his own use as a supplement to the steam power, we must, in a comparison of the costs, consider the losses involved, but only those losses which occur from the plant through the 10 kV net, because the wind-generated electricity must also be distributed and must also undergo a loss in the 10 kV line network. The "primary" loss is 4%, according to previous experience.

If, on the other hand, we assume that the wind power plant is built on a larger scale in order to cover an increase in the consumption of electricity, then we cannot simply assume that the wind-generated electricity can be bought where it is produced. In this case, we must consider that this electricity -- like the steam-powered electricity from a cooperative power works group -- shall be transmitted over longer distances through the primary high tension system. In this case, one can compare the costs of the two types of production, steam and wind power respectively, without consideration of the loss factor.

4.0.7. Reserve Power Problems

An important question in the evaluation of wind-generated electricity's value is the problem of reserve power. Can we count upon the rated wind power output to be a certain percent below maximum, and, if we can count on it, how much?

In order to clarify to what extent we can count upon wind energy, and thereby wind output, to be available during the electrical plant's maximum load, we have worked out the listings on the following pages, on the basis of information in "Danish Electrical Power Statistics 1959/60", Elsam and IFV-SEAS, concerning the maximum load interval for each of the major power plant's consumer area in 1959/60, and also concerning the maximum load interval over a number of years for Elsam and IFV-SEAS, together with information obtained from the Meterological Institute concerning weather and wind conditions for the places and time periods in question.

The Gedser windmill is designed to begin rotation when the wind strength is approximately 5 m/sec, which corresponds to a

DIAGRAM 1. ELSAN, SKÆRBÆK PR. FREDERICIA

Yearly maximum loading:	Meteorological station	8:00 Temp.	8:00 Wind	14:00 Temp.	14:00 Wind	21:00 Temp.	21:00 Wind
1957/58	Fredericia	- 3.6	SSE 3	- 3.0	S 3	- 0,9	SW 4
	Gråsten	- 6.5	SSW 2	- 4.7	SE 2	- 2,3	SW 1
379 MW - 18 December 1957	Svenstrup	- 5.1	S 1	- 3.2	SE 2	- 3.4	SE 2
	Højbjerg	- 5.2	S 2	- 4.6	S 3	- 2.4	S 4
8:15	Hanstholm (Time 7-13-19)	- 3.8	S 3	- 4.8	SSE 4	- 4.2	SSE 4
	Hirtshals Fyr	–	S 2	–	S 3	–	S 2
	Blangstedgaard	- 5.3	SSE 3	- 3.6	SSE 2	- 2.0	SSE 2
1958/59	Fredericia	3.9	WSW 4	5,9	W 4	5,5	W 4
	Gråsten	3.8	W 3	5,5	W 3	5.6	W 3
436.5 Mw - 16. January 1958	Svenstrup	3.8	W 3	4,7	W 4	5.2	W 4
	Højbjerg	3.6	W 4	5.0	W 3	4,4	SW 5
8:20	Hanstholm (Time 7-13-19)	4,8	W 4	4.9	WSW 3	5,4	WSW 5
	Hirtshals Fyr	–	W 4	–	WSW 4	–	W 4
	Blangstedgaard	3.1	SSW 3	5,6	WSW 4	5,1	WSW 5
1959/60	Fredericia	2.7	S 4	4,8	S 4	7,1	SW 4
	Gråsten	3.2	WNW 2	5.2	W 4	7.7	W 2
491.3 Mw - 17. December 1959	Svenstrup	1.6	S 1	2.5	S 2	5,7	SSW 2
	Højbjerg	1.4	SSE 5	3.4	S 5	6.0	SW 6
17:15 - 17:30	Hanstholm(Time 7-13-19)	0.2	S 5	2.2	SSE 5	6.8	SW 5
	Hirtshals Fyr	–	S 3	–	S 4	–	S 5
	Blangstedgaard	2.0	SSE 4	4.5	SSE 5	6.5	S 5
1960/61	Fredericia	2.6	NW 2	3,2	NW 2	1,2	NW 2
	Gråsten	2,4	W 2	2.7	W 2	1.8	W 1
553 Mw - 21. December 1960	Svenstrup	4.2	S 2	5,0	S 3	4.1	S 4
	Højbjerg	2.4	NE 3	2.4	NNE 2	1,8	N 2
8:15 - 8:30	Hanstholm (Time 7-13-19)	3.5	NE 3	4.5	ENE 3	3,9	NE 3
	Hirtshals Fyr	–	ENE 2	–	E	–	0
	Blangstedgaard	3.3	NNW 1	3.8	NNW 2	3.8	0

Note: Hirtshals lighthouse does not measure temperature.

DIAGRAM 2. IFV-SEAS, SJÆLLAND

Yearly maximum loading	Meteorological station	8:00 Temp.	8:00 Wind	14:00 Temp.	14:00 Wind	21:00 Temp.	21:00 Wind
1957/58 293.6 MW - 17 December 1957 17:30 - 18:00	Tystofte Kalundborg Landbohøjskolen	- 2.3 - 1.5 - 3.2	S 1 S 2 SW 1	- 2,1 - 1,5 - 1,8	S 1 SW 1 SW 2	- 3.5 - 3.5 - 4.0	E SE W
1958/59 312.3 MW - 16 December 1958 17:30 - 18:00	Tystofte Kalundborg Landbohøjskolen	2.1 3.5 4.0	E 3 E 2 E 3	2.0 3,6 4.2	E 3 SE 2 SE 3	2.8 3,7 4.6	E SE SE
1959/60 362.1 MW - 13 January 1960 17:30 - 18:00	Tystofte Kalundborg Landbohøjskolen	- 7.5 - 8.0 - 5.6	NE 3 E 2 ENE 3	- 5.4 - 4,0 - 5.2	NNE 4 NE 4 NE 3	- 4.6 - 3.1 - 4.1	NNE ENE NE
1960/61 382,4 MW - 13 December 1960 17:00 - 17:30	Tystofte x) Kalundborg Landbohøjskolen	 2.8 1.6	 SSW 2 SW 1	 2.6 2.0	 SW 1 SW 1	 2,4 2,4	 SW E

x) Station's data has been loaned out.

wind strength of 3 or 4 Beaufort, and it will operate at maximum efficiency when the wind speed is 15 m/sec, which corresponds to 7 Beaufort.

In Diagrams 1 and 2, we see the following:

The maximum wind strength for Elsam was 3 or less in 1957/58 and 1960/61, and this was also the case for the IFV-SEAS in 1957/58, 1958/59 and 1960/61.

Of the 10 major power plant's consumer areas we found that six had yearly maximums of 3 or less, in 1959/60.

[Next paragraph missing in original document]

4.0.8. Wind Power Plants Used as a Supplement to the Steam Power Plants /72

If wind power plants are built on only a small scale, as a supplement to the steam power plants, then no money can be saved on the steam power plants in capital expenditures, repairs, maintenance, and operating expenses. The wind-generated electricity can therefore only be paid for with the savings on fuel use, with the addition of the transmission loss factor.

The cost of wind energy (5.1) is here compared with the steam power work's fuel savings of q_g = 3100 kcal/kWh net (see 5.2.2), with the addition of a 4% transmission loss factor.

$$8.0: \quad 7.82 \times \alpha + 1 = \frac{10^{-4} q_g \times C}{0.96} = 0.323\ C\ \text{øre/kWh}$$

which can also be expressed:

$$8.1: \quad C = 24.20 \times \alpha + 3.10\ \text{kr/Gcal}.$$

4.0.9. Construction of Wind Power Plants Instead of Steam Power Plants

If wind power plants are built on a large scale, instead of steam power plants, in order to cover a growth in the demand for electricity, then the most important stipulations will be that the wind-generated electricity is available whenever it is needed, every day of the year, and also, that the electricity can be used when it is produced.

Provided that these stipulations could be satisfied, we could then continue to a comparison of the cost for wind energy (see 5.1) with the cost for steam power from new plants (see 5.2.1):

9.0: $7.82 \times \alpha + 1 = 2.70 + 0.25 \times C$ øre/kWh

which can also be expressed:

9.1: $C = 31.28 \times \alpha + 6.8$ kr/Gcal

It is immediately clear that the stipulations for 9.0 cannot be satisfied in practice. The size of the electricity demand fluctuates greatly from hour to hour within each day, and we must also consider the seasonal variations, that is, greater demand for electricity during the winter than during the summer. It is not necessary to illustrate further that the wind energy is not always available at the same time as the demand is present, if one simply remembers that it is quite possible for a dead calm to last several days.

However, wind power plants in Denmark will be built in conjunction with the existing steam power plants, which means that the system as a whole can always deliver the electrical energy which is needed by using either steam or wind, depending upon the wind strength of each particular day. /73

During the maximum load period -- and especially during the year's highest load -- the steam power plants will be completely taxed, except for the output reserve which is necessary to compensate in the case of boilers or machinery trouble, and these plants would therefore not be able to assist the windmills, if there happened to be still weather during the maximum load period (see considerations in Enclosure 4.0.7. concerning reserve power problems).

As a consequence, we must set up reserve power works in conjunction with the wind powerworks, so that these can take over during those times of the day and year when the wind power does not yield a sufficiently high output to cover its share of the joint system's maximum output.

According to our calculations, these reserve power plants would only be needed for short intervals, and they could therefore be built as gas turbine generators capable of 500-1000 hours of yearly operational time. According to our information, these generators could probably not be built for less than 600 kr/kW, and the yearly expenditures for operation and maintenance would be 6 kr/kW.

With a rate of interest of 6% per year and amortization over 25%, a yearly expenditure per kW of reserve output will be:

$$0.0782 \times 600 + 6 = 53 \text{ kr.}$$

Since it has been shown that there is considerable risk that, during the year's maximum load, there will be little or no wind power available -- see Enclosure 4.0.7 -- it will be necessary to consider a reserve output corresponding to 100% of the wind power's share of the maximum load. According to Enclosure 4.0.2., the utilization time for the maximum load is 4000 hours, and the expenditures per kWh of reserve power then become:

$$53/4000 = 1.3 \text{ øre/kWh.}$$

If we increase the wind power's cost (5.1) at this rate, we can then compare this corrected cost with the cost for steam-generated electricity from new plants (5.2.1), because there will now be compensation for electricity energy as well as electrical output on both sides of the comparison.

9.2: $7.82\alpha + 1 + 1.3 = 2.7 + 0.25\ C,$

which can also be expressed:

9.3: $C = 31.28\alpha \div 1.6$ kr/Gcal.

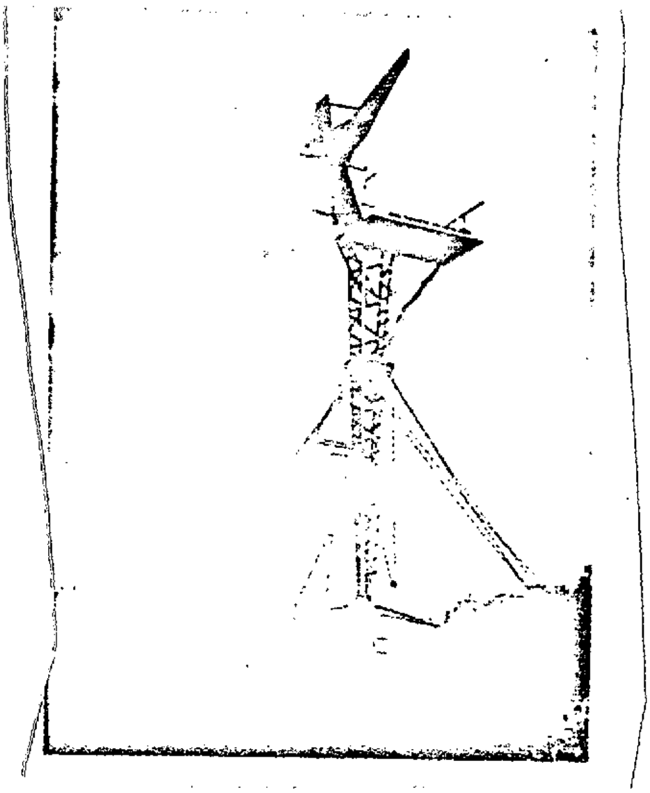


Fig. 1. SEAS' test windmill in western Egesborg. Swept area 45 m^2, diameter 7.6 m - 13 kW - 38 m/sec wing-tip speed.

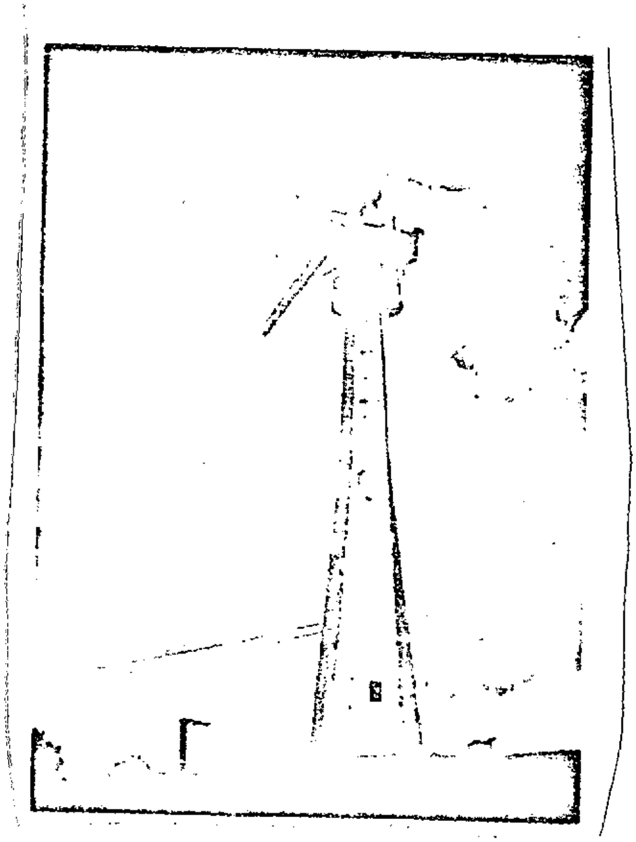


Fig. 2. SEAS' test windmill at Boge. Swept area 132 m^2, diameter 13 m - 45 kW - 38 m/sec wing-tip speed.

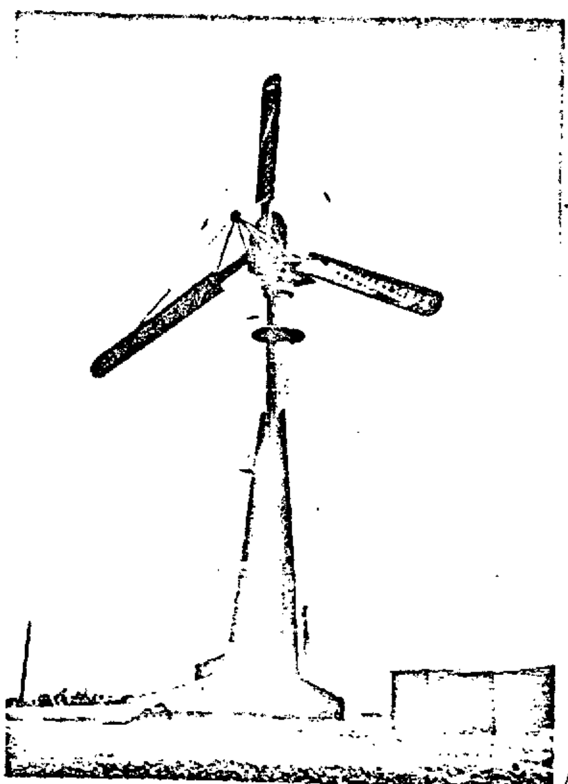


Fig. 3. Gedser windmill.

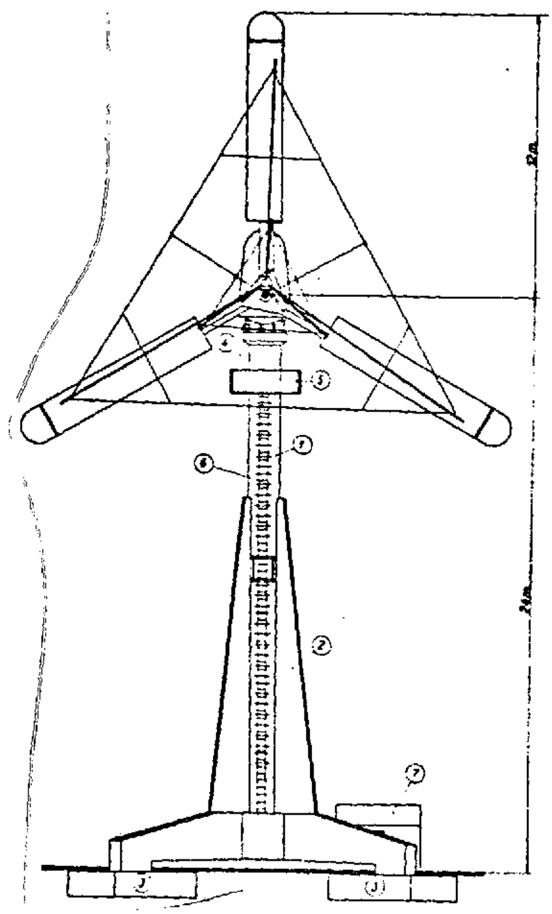


Fig. 4. Gedser windmill. Swept area 450 m^2, diameter 24 m - 200 kW - 38 m/sec wing tip speed.

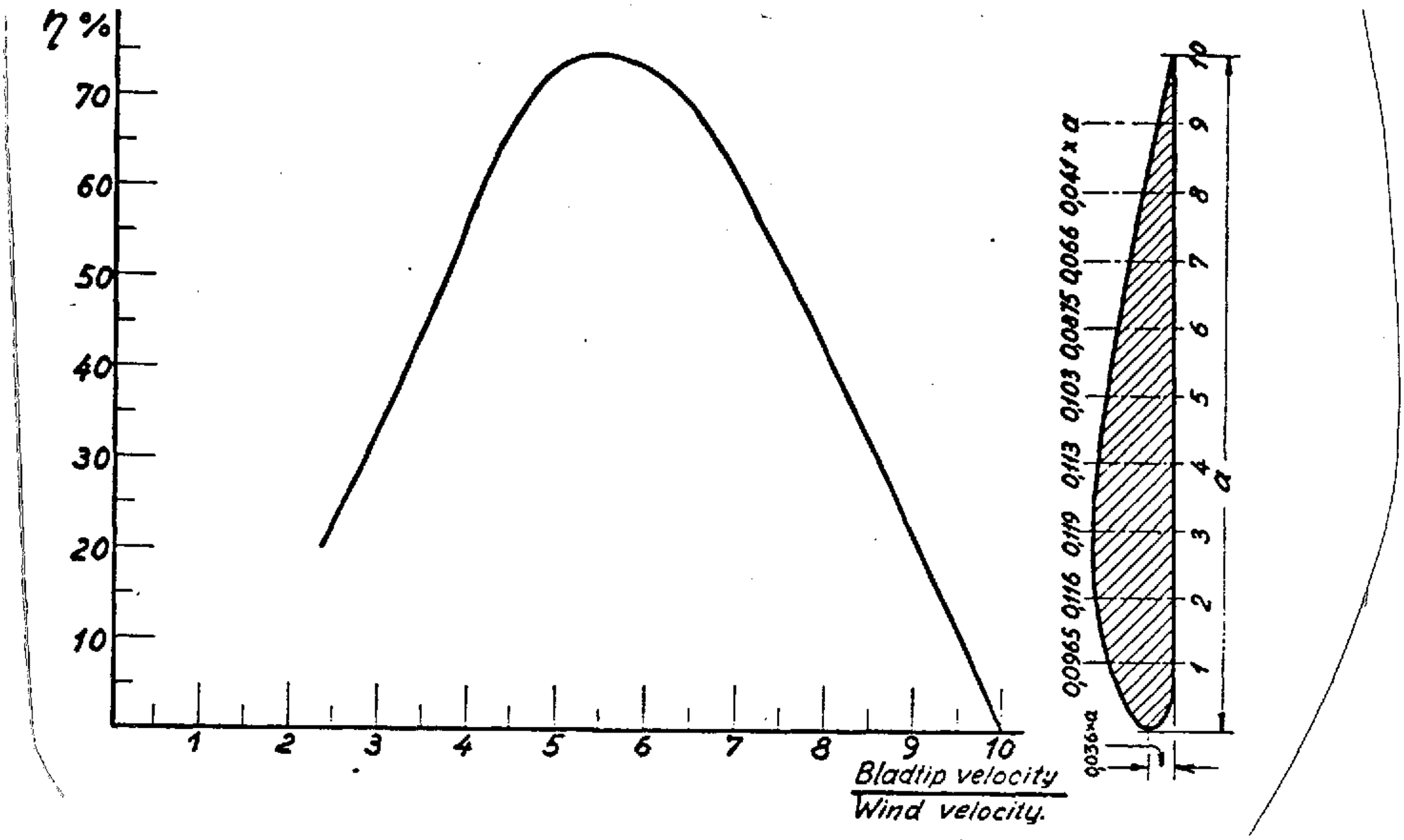


Fig. 5. Sail profile and curve over efficiency degrees determined by model testing. Valid for wind speed 6 m/sec.

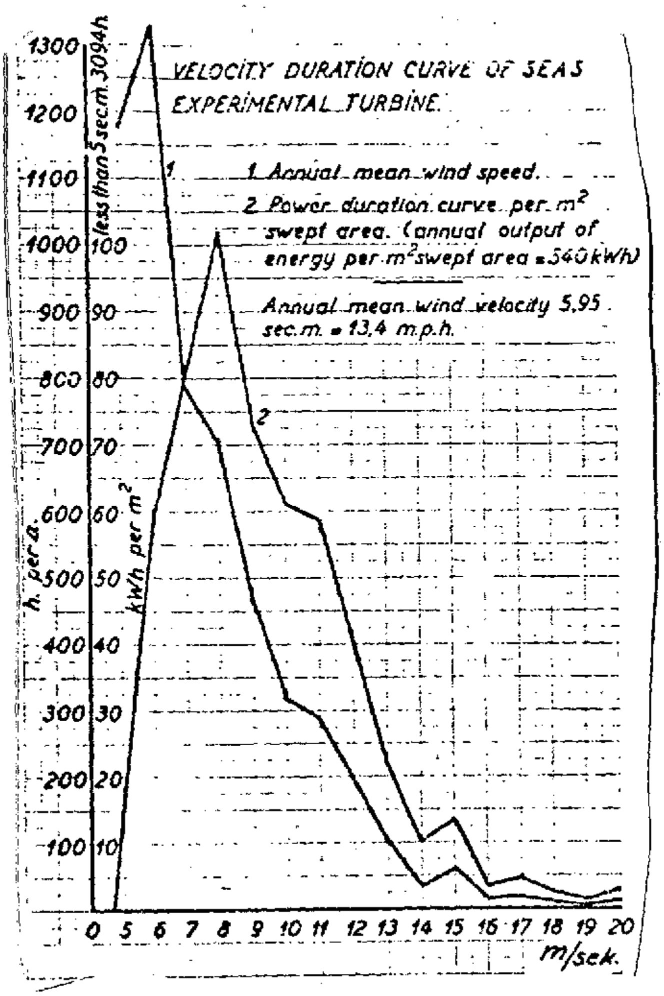


Fig. 6. Curve 1. Average yearly wind speed 5.95 m/sec measured at western Egesborg windmill. Curve 2. Calculated yearly production 540 kWh/m^2 swept area. Measured production in 1953: 525 kWh/m^2 swept area.

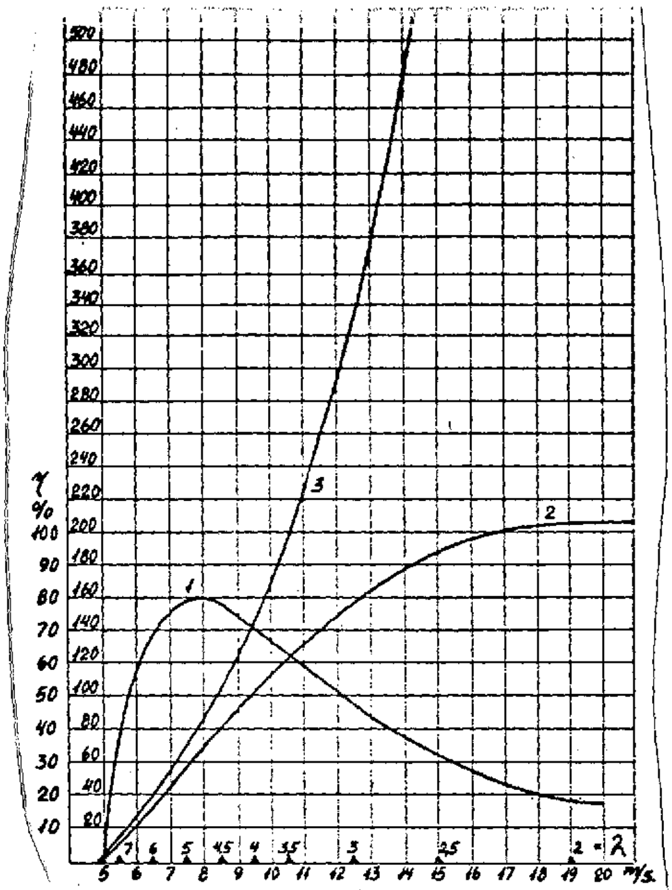


Fig. 7. Curve 1. Gedser mill's effective degree (exclusive transmission loss?). Curve 2. Gedser mill's output. Curve 3. Wind energy calculated according to the formula D^2 x V x V^3 x 0.000285, with d = 24 m.

$\frac{1}{2} \rho \cdot \frac{\pi}{4} \cdot \frac{16}{27} = \frac{1}{2} \cdot 1.22 \cdot \frac{\pi}{4} \cdot \frac{16}{27} \quad 10^{-3}$ kW

that is, the energy which the ideal windmill can utilize.

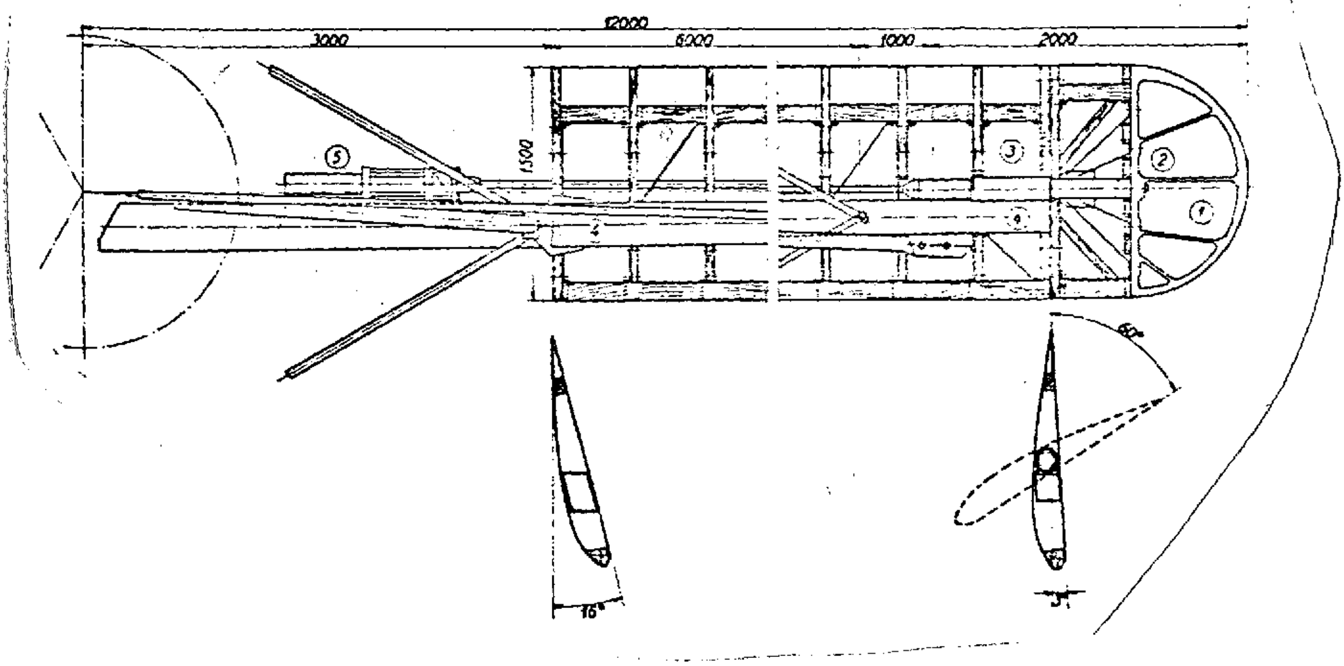


Fig. 8. Gedser windmill's sail construction.

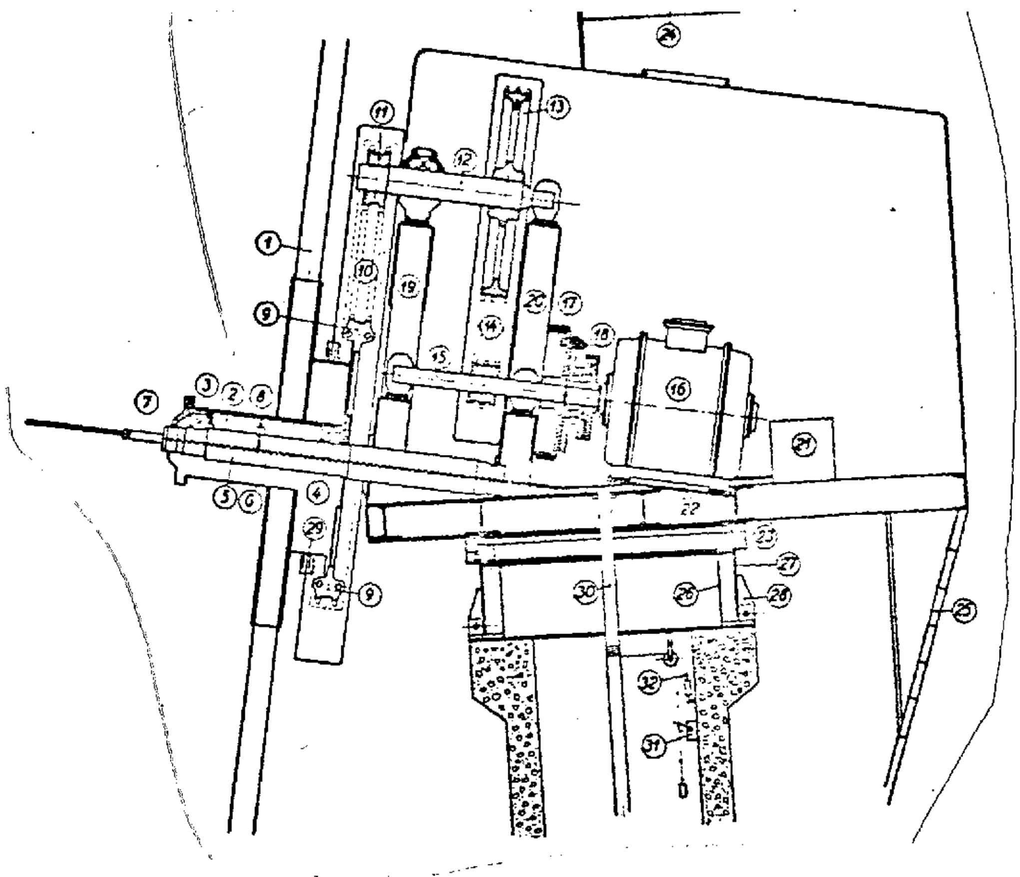


Fig. 9. Construction of machinery cabin.

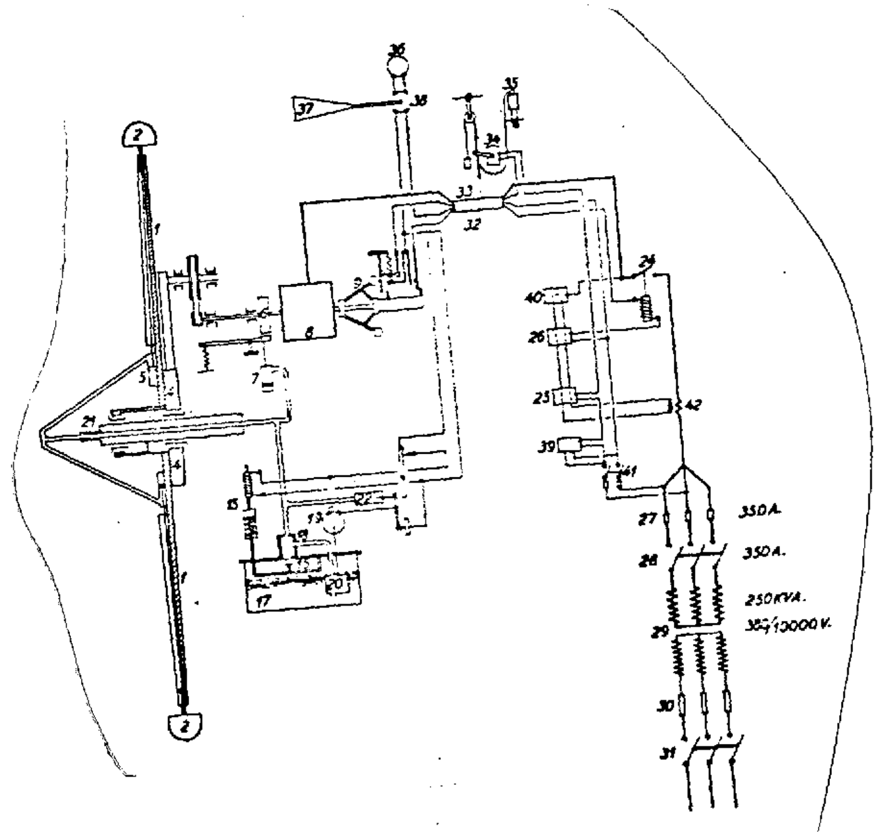


Fig. 10. Mechanical and electrical function diagram.

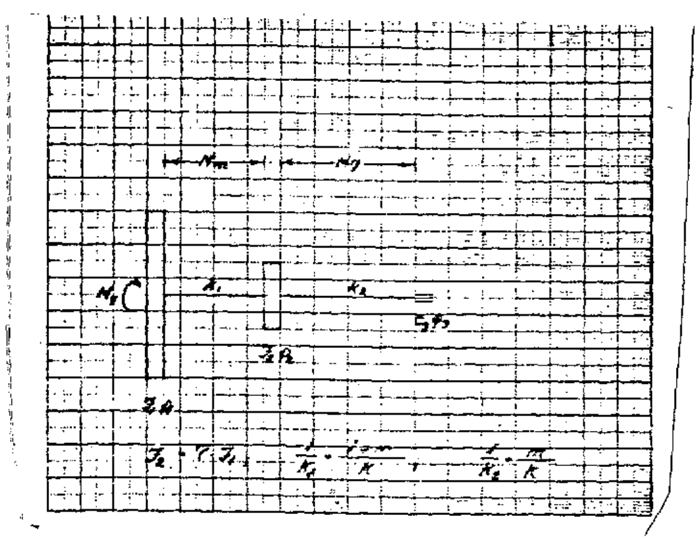


Fig. 11.

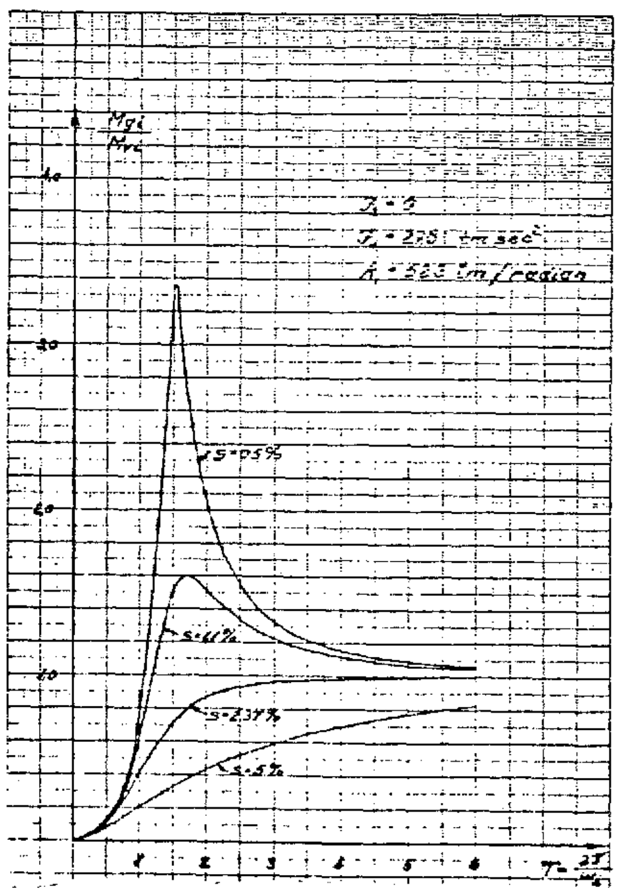


Fig. 12.

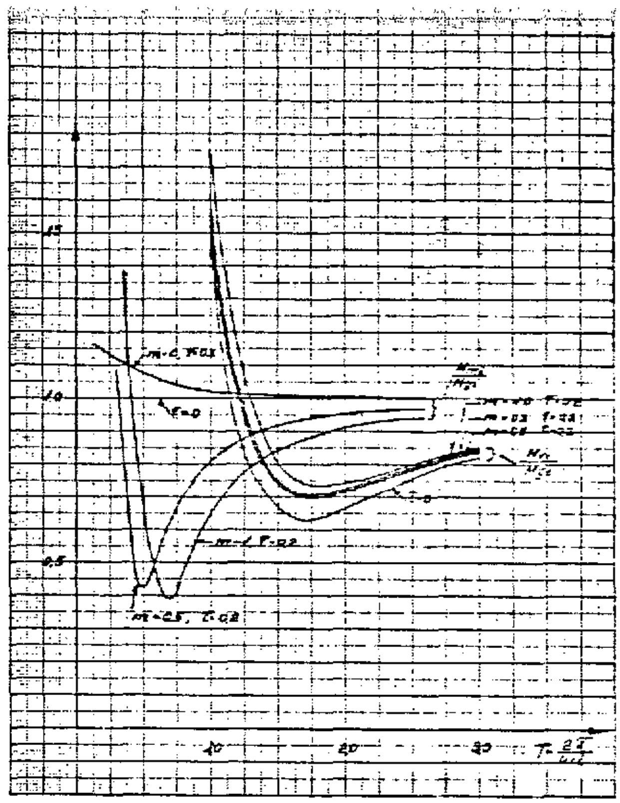


Fig. 13.

Fig. 13.

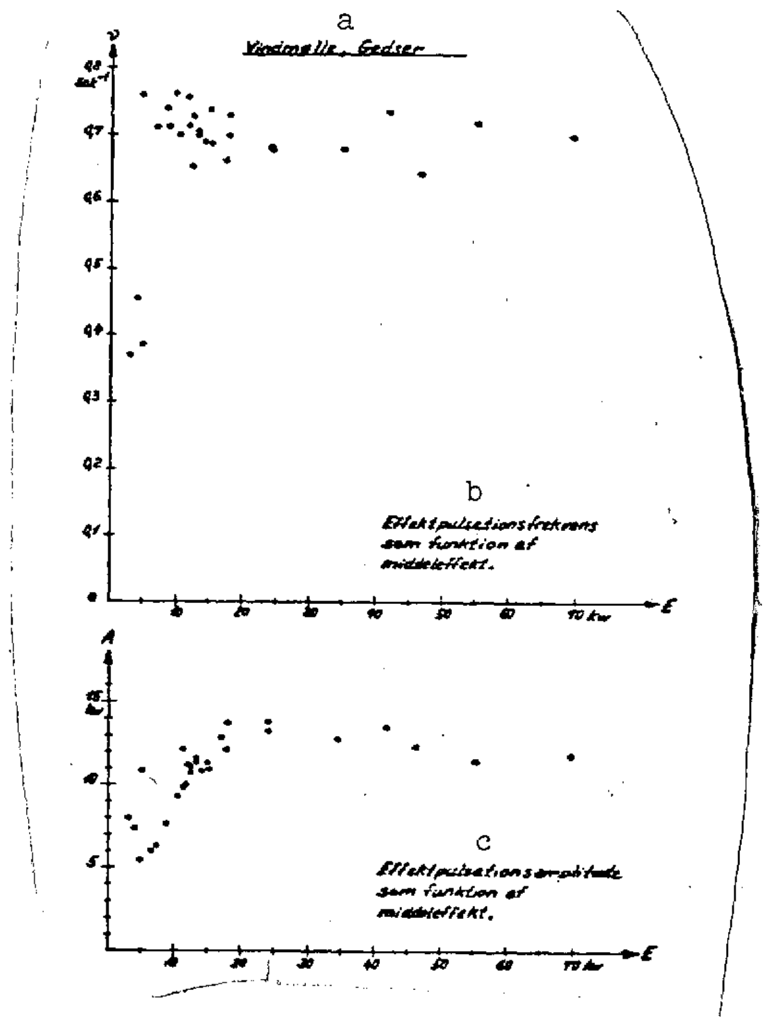


Fig. 14.

Key: a. Windmill, Gedser
b. Power pulsation frequency as a function of mean power
c. Powerpulsation amplitude as a function of mean power.

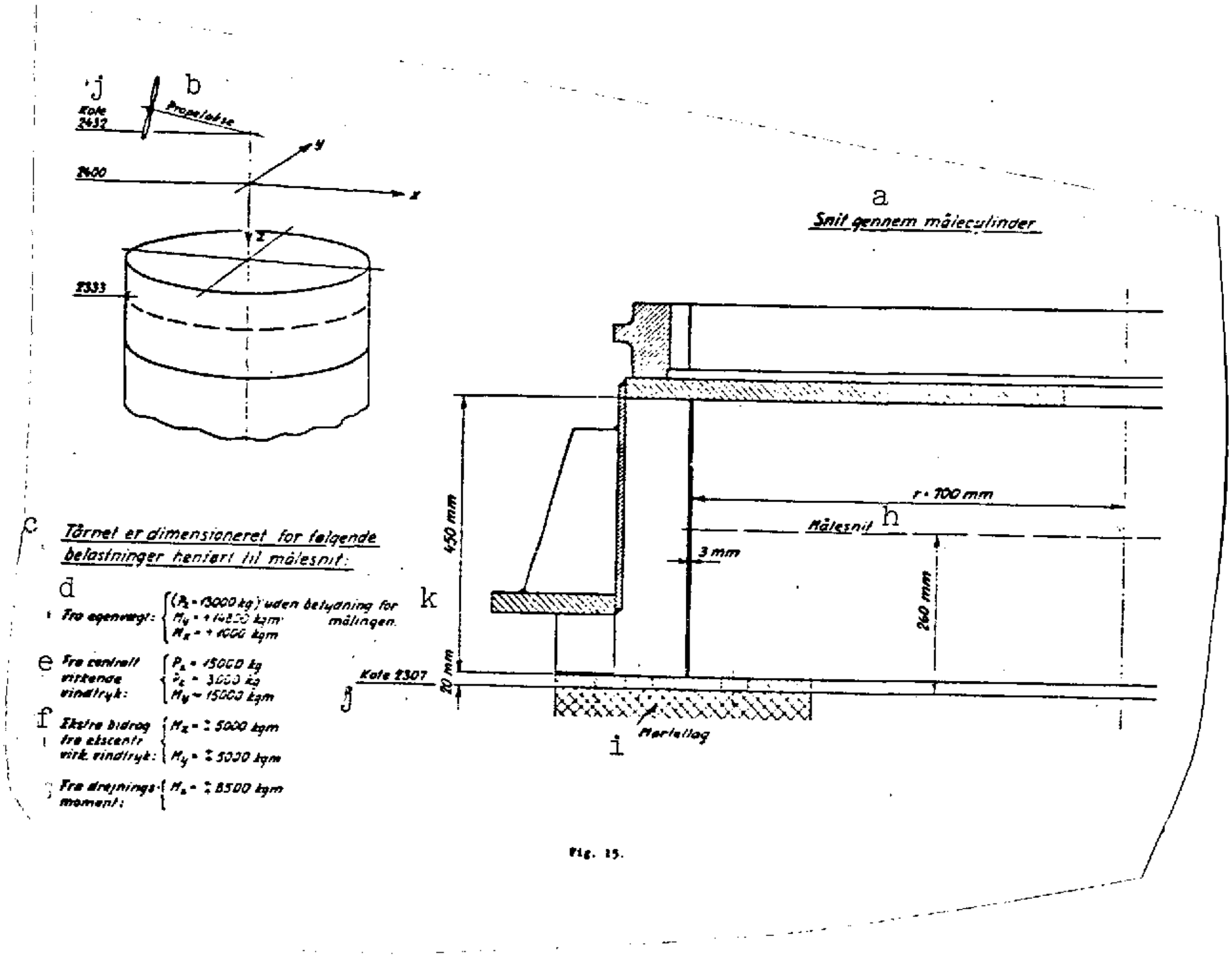


Fig. 15.

Key:
- a. Section through measuring cylinder
- b. Propeller axis
- c. Tower is dimensioned for the following loads transferred to the measuring section:
- d. From net weight:
- e. From centrally effective wind pressure:
- f. Extra contribution from eccentrically effective wind pressure:
- g. From turning moment:
- h. Measuring section
- i. Mortar layer
- j. Level
- k. Without meaning for the measurement

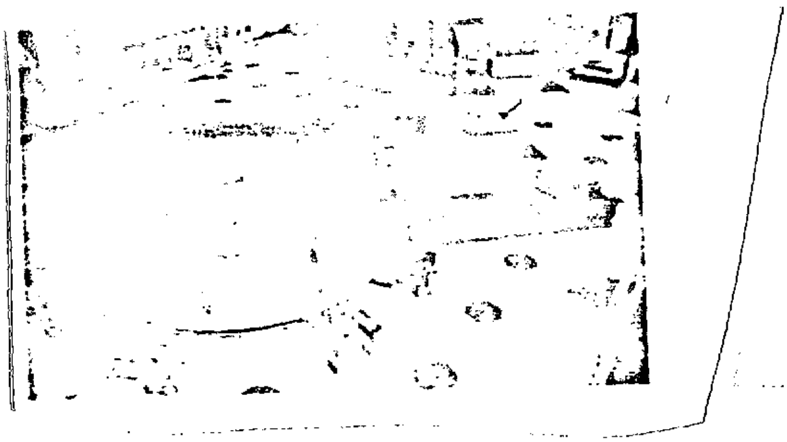


Fig. 16

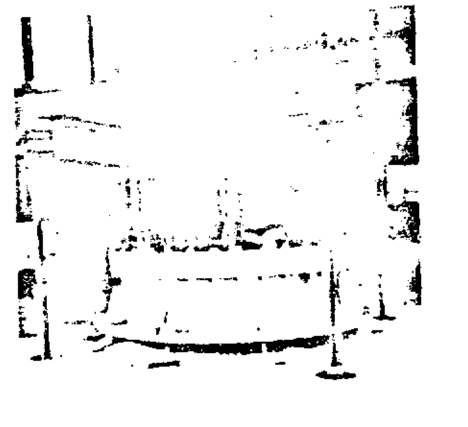


Fig. 17

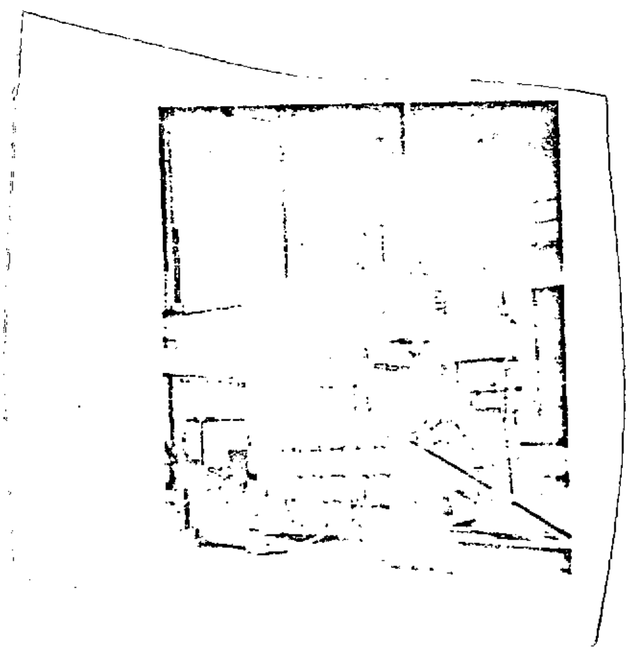


Fig. 18

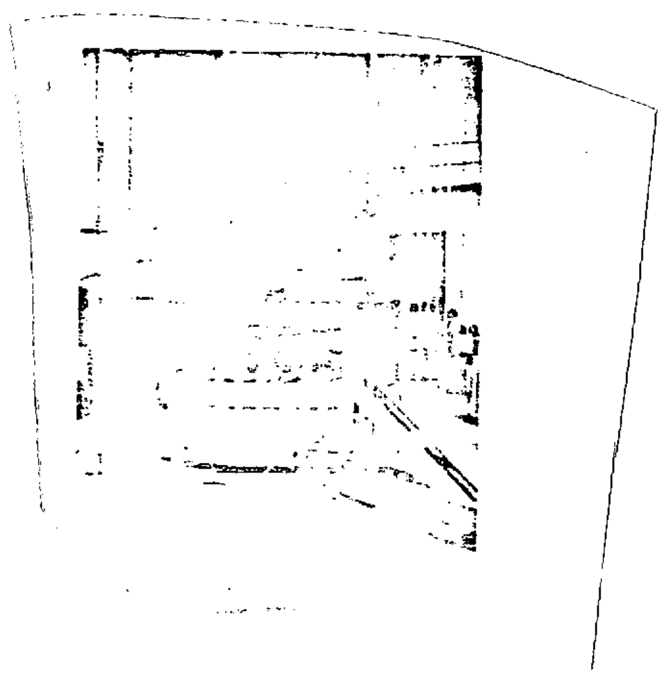


Fig. 19

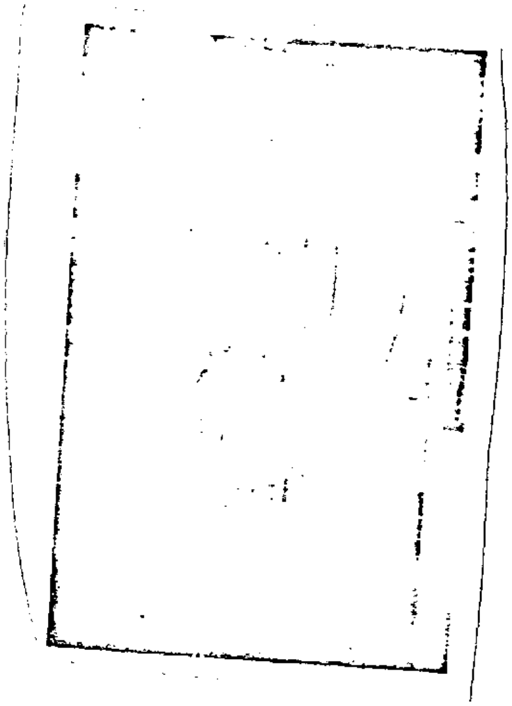


Fig. 20

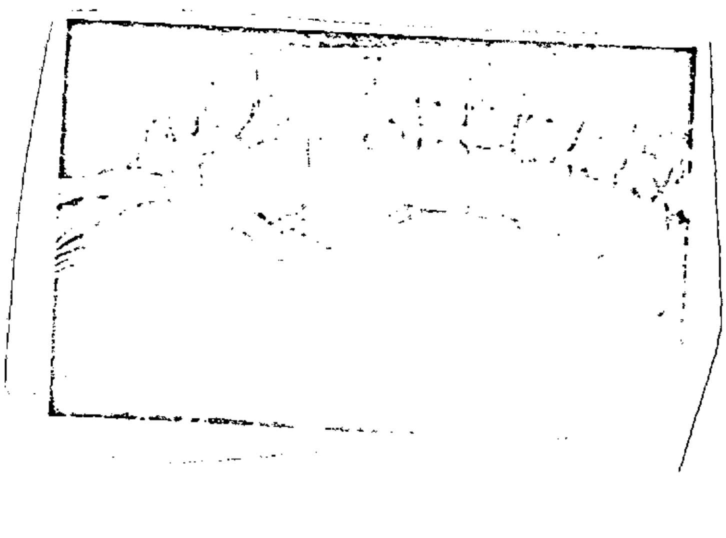


Fig. 21

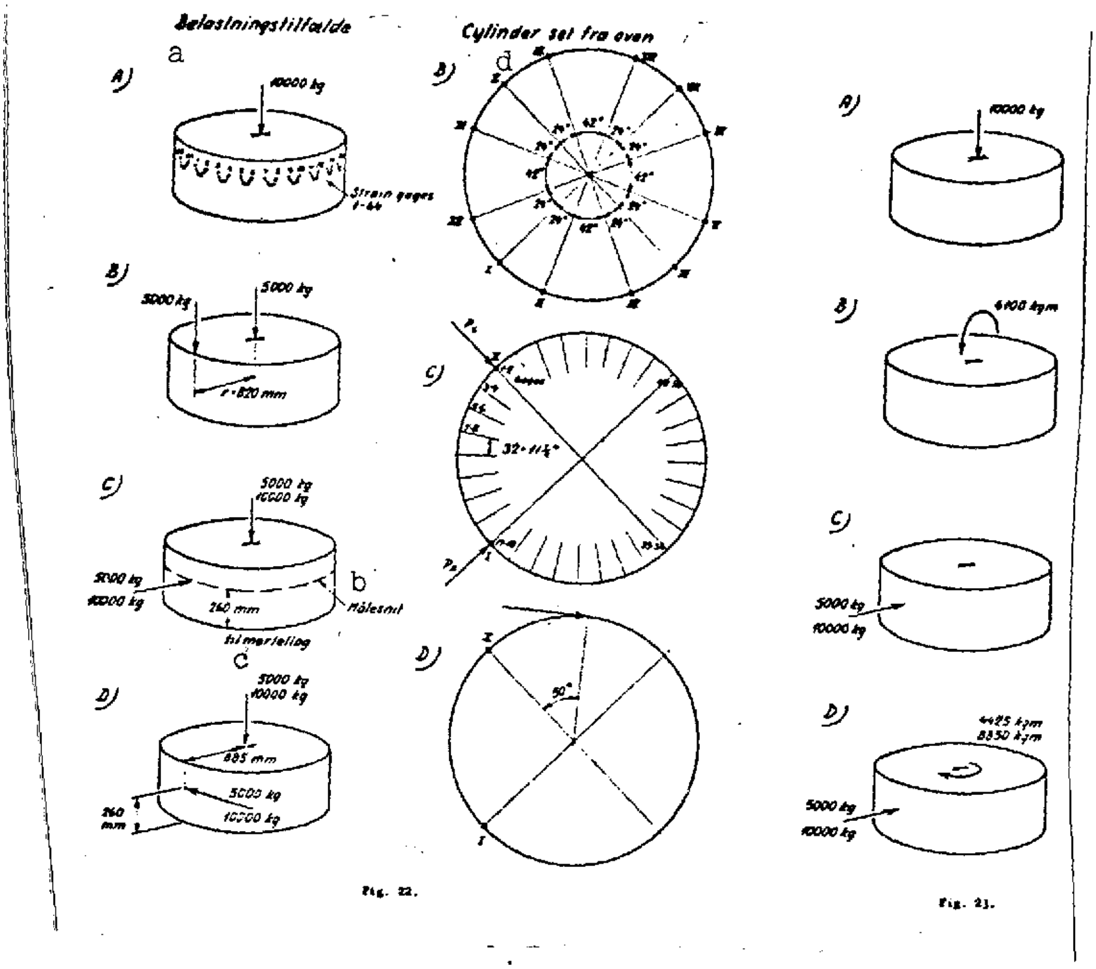


Fig. 22

Fig. 23.

Key:
- a. Load instances
- b. Measuring section
- c. To mortar layer
- d. Cylinder seen from above

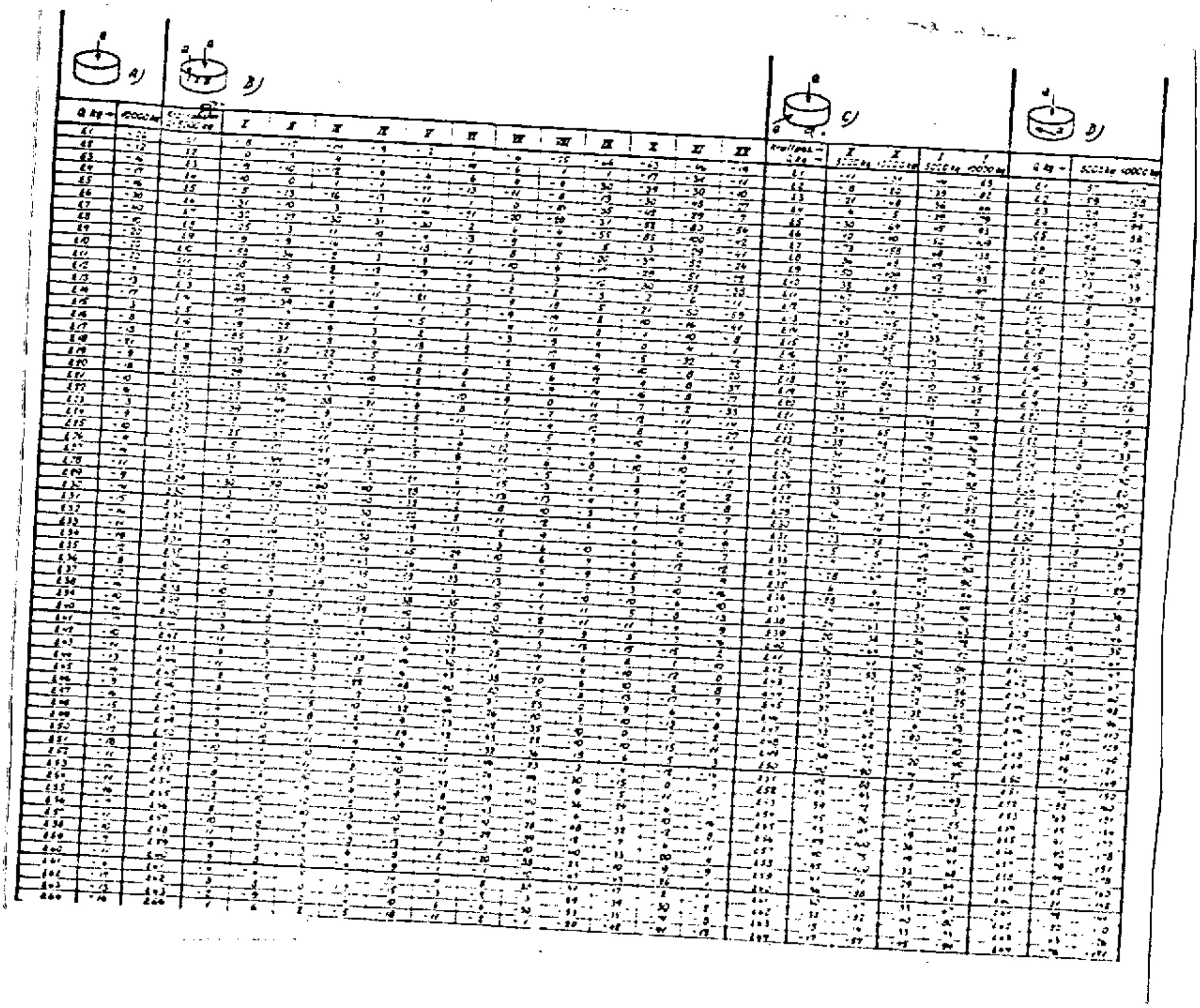


Fig. 24.

Key: a. Power pos.

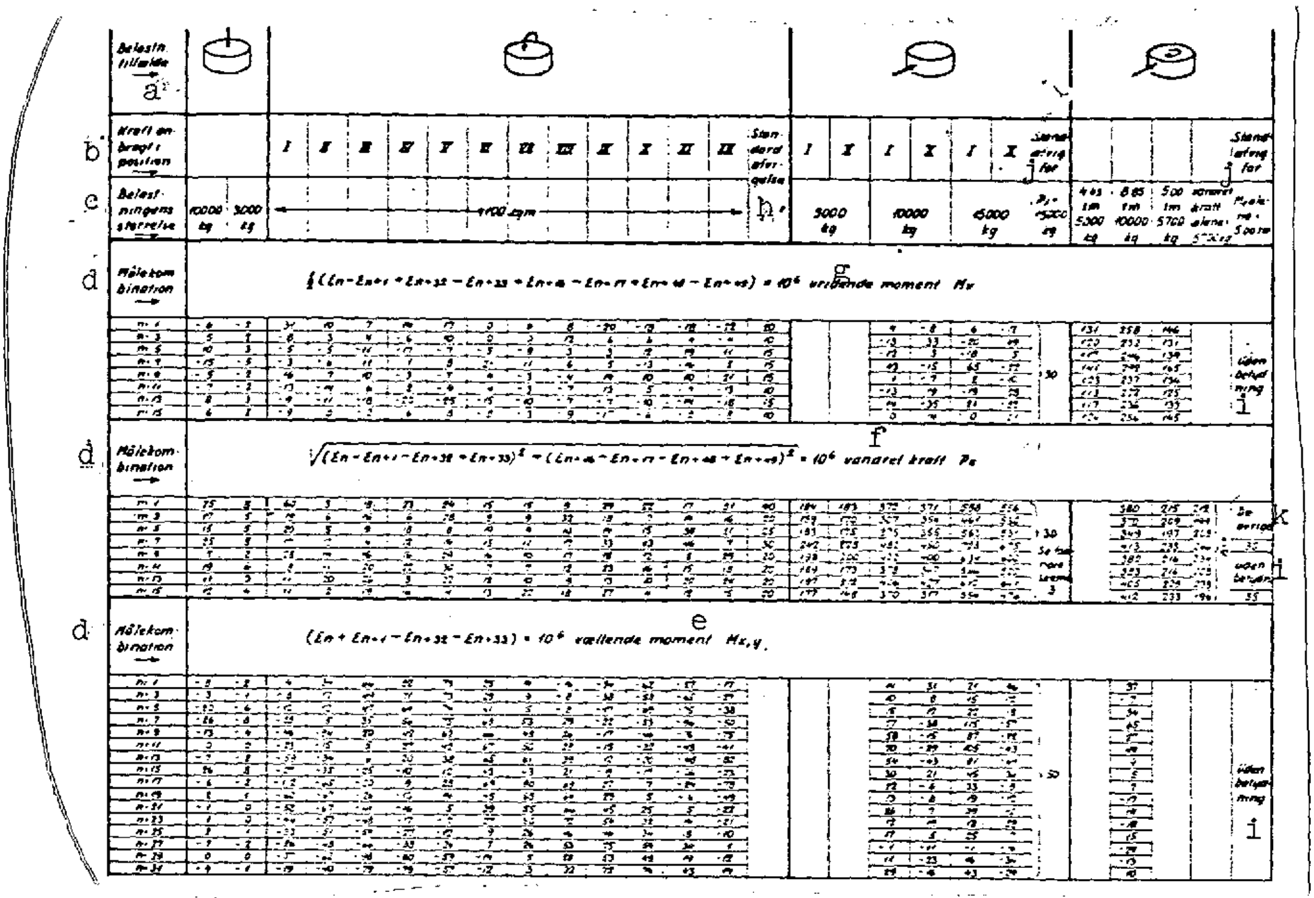


Fig. 25.

Key:
a. Load instants
b. Power placed in position
c. Loads size
d. Measuring combination
e. Overturning moment
f. Horizontal power
g. Torsional moment
h. Standard deviation
i. Of no meaning
j. Standard deviation for
k. The above

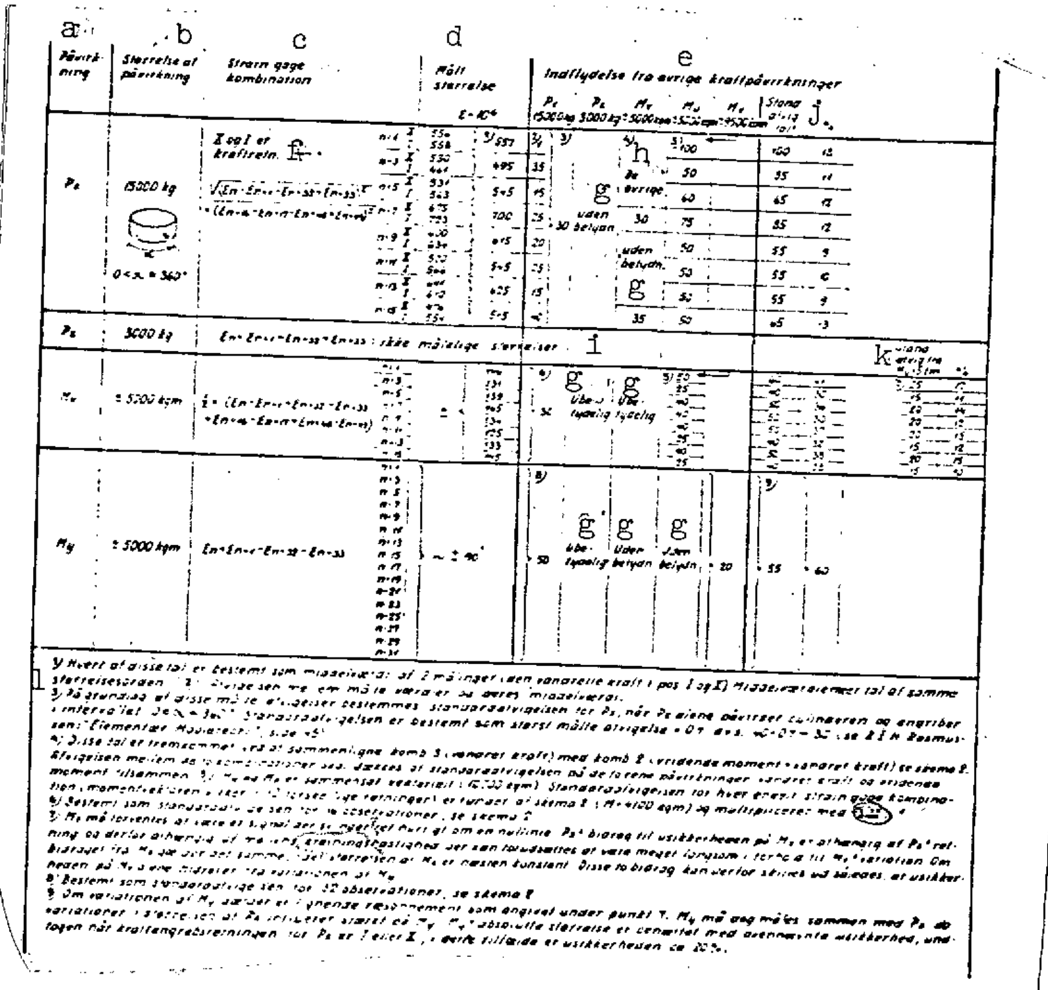


Fig. 26.

Key: a. Effect
b. Size of effect
c. Strain gauge combination
d. Measured size
e. Influence of all of the power effects
f. X and I are power directions.
g. Of no meaning
h. The above
i. No measurable values
j. Standard deviation total
k. Standard deviation from $M_y \cdot 50$tm
l. 1) Each of these values is determined as the mean value of two measurements (the horizontal energies in positions I and X). The middle values are of the same order of magnitude. 2) Deviation between measured values and their average values. 3) On the basis of these measured deviations the standard deviation is determined for P_x, when P_x alone influences the cylinder and strikes in the interval $0 < \alpha < 360$. The standard deviation is
[Key continued on following page]

Key to Fig. 26, continued

1. determined as the largest measured deviation = 0.7% in other words 40·0.7 - 30 (see REM Rosmus: "Elementary measurement theory", p. 45). 4) This value is arrived at by comparing combination 3) (horizontal energy) with combination 2 (torsional moment-horizontal energy), see diagram 2. The deviation between these two combinations shall be covered by the standard deviation of the two pure effects, horizontal power and the torsional moment together. 5) M_y and M_x are combined vectors (10,700 kg). The standard deviation for each individual strain gauge combination (moment vector effective in two different directions) is found in diagram 2 (M = 4100 kg) and multiplied with [illegible]. 6) Determined as the standard deviation for 16 observations, see diagram 2. 7) M v must be expected to be a signal which swings rapidly around a null line. The contribution of $P_x{}^3$ to the uncertainty of M_y is dependent upon the direction of P[illegible] 4, and therefore dependent upon the windmill's yaw speed, which can be assumed to be very slow in relation to the fluctuation of M_y3. The same is true for the contribution of M_z. (This value of M_z is almost constant. These two contributions can therefore be differentiated in that the uncertainty of M_y alone concerns the variation of M_y. 8) Determined as the standard deviation for 32 observations, see diagram 2. 9) A similar argument to that presented under point 7 is valid concerning the fluctuations of M_y. Nevertheless, M_y must be measured together with P_x, two variations in the size of P_x exert a strong influence upon M_y. M_y times the absolute value entails the above-mentioned uncertainty, except for when the power attack direction for P_x is I or X, in which case the uncertainty is around 20%.

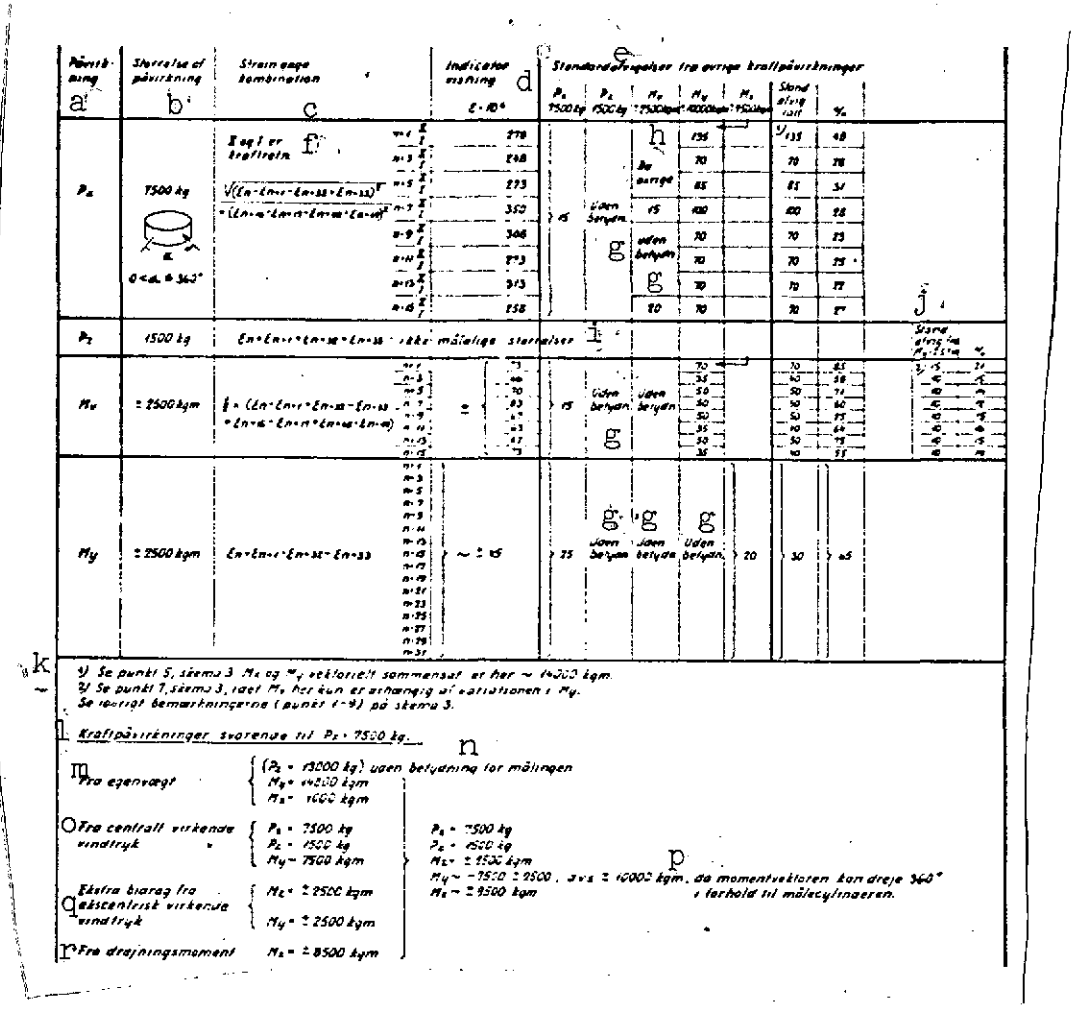


Fig. 27.

Key: a. Effect
b. Size of effect
c. Strain gauge combination
d. Indicator reading
e. Standard deviations from other power effects
f. X and I are power direction
g. Without meaning
h. The above
i. ... nonmeasurable values
j. From M_y = 25 tm
k. 1) see point 5, diagram 3. M_x and M_y vectorially combined are approximately equal to 14,000 kg.
2) see point 7, diagram 3, in that M_y here is only dependent upon variation of M_y. See the other notes (points 1 through 9) in diagram 3.
l. Power effects corresponding to P_x = 7500 kg
m. From net weight
n. Of no meaning for the measurement

[Key continued on following page]

Key to Fig. 27, continued

o. From centrally effective wind pressure
p. In other words, ±10,000 kgm, when the moment vector can rotate 360° in relation to the measuring cylinder
q. Extra contribution from eccentrically effective wind pressure
r. From torque moment

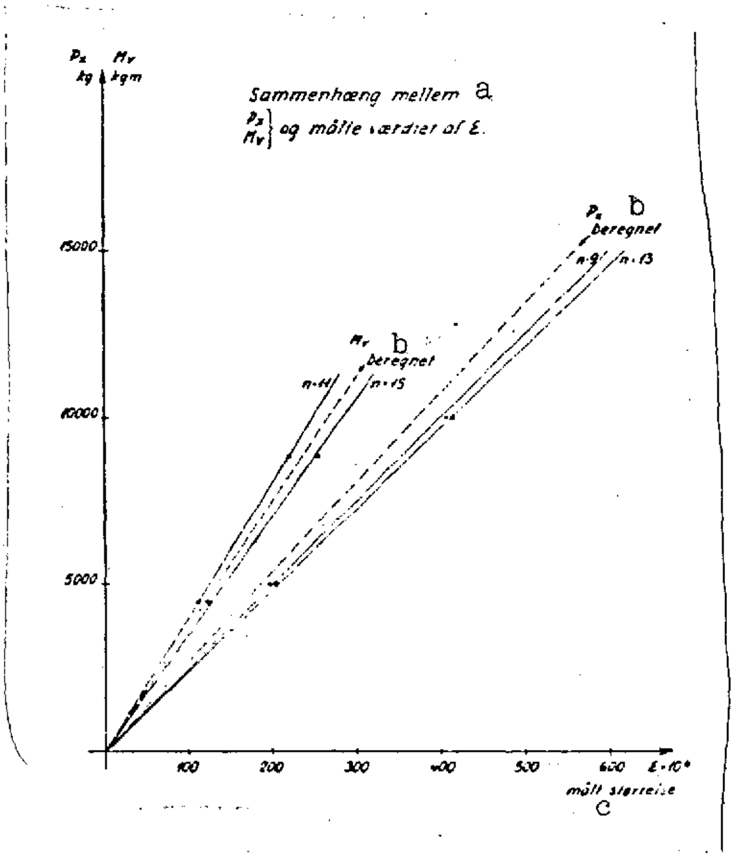


Fig. 28

Key: a. Connection between $\left.\begin{matrix}V_x\\M_v\end{matrix}\right\}$ and the measured values of ε
b. Calculated
c. Measured values

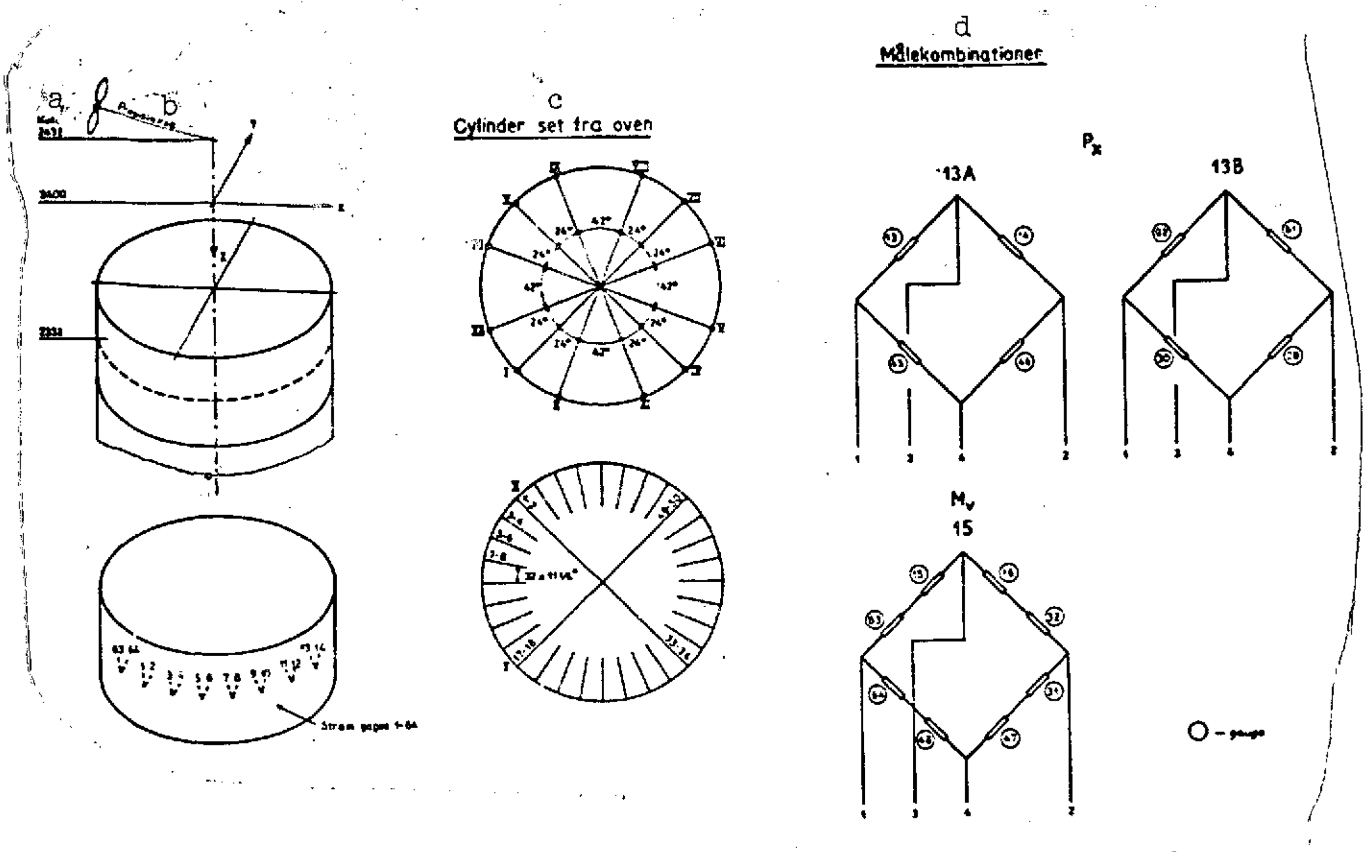


Fig. 29.

Key: a. Level
b. Propeller axis
c. Cylinder seen from above
d. Measuring combinations

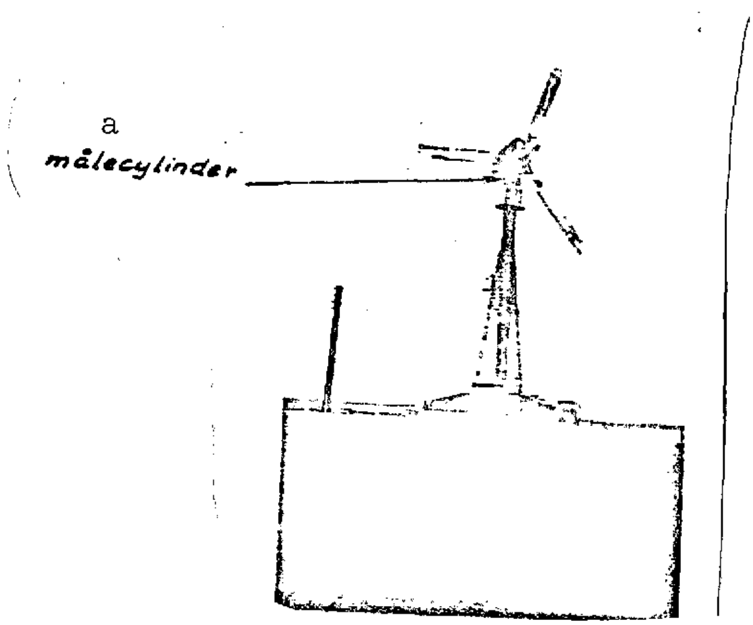


Fig. 30.

Key: a Measuring cylinder

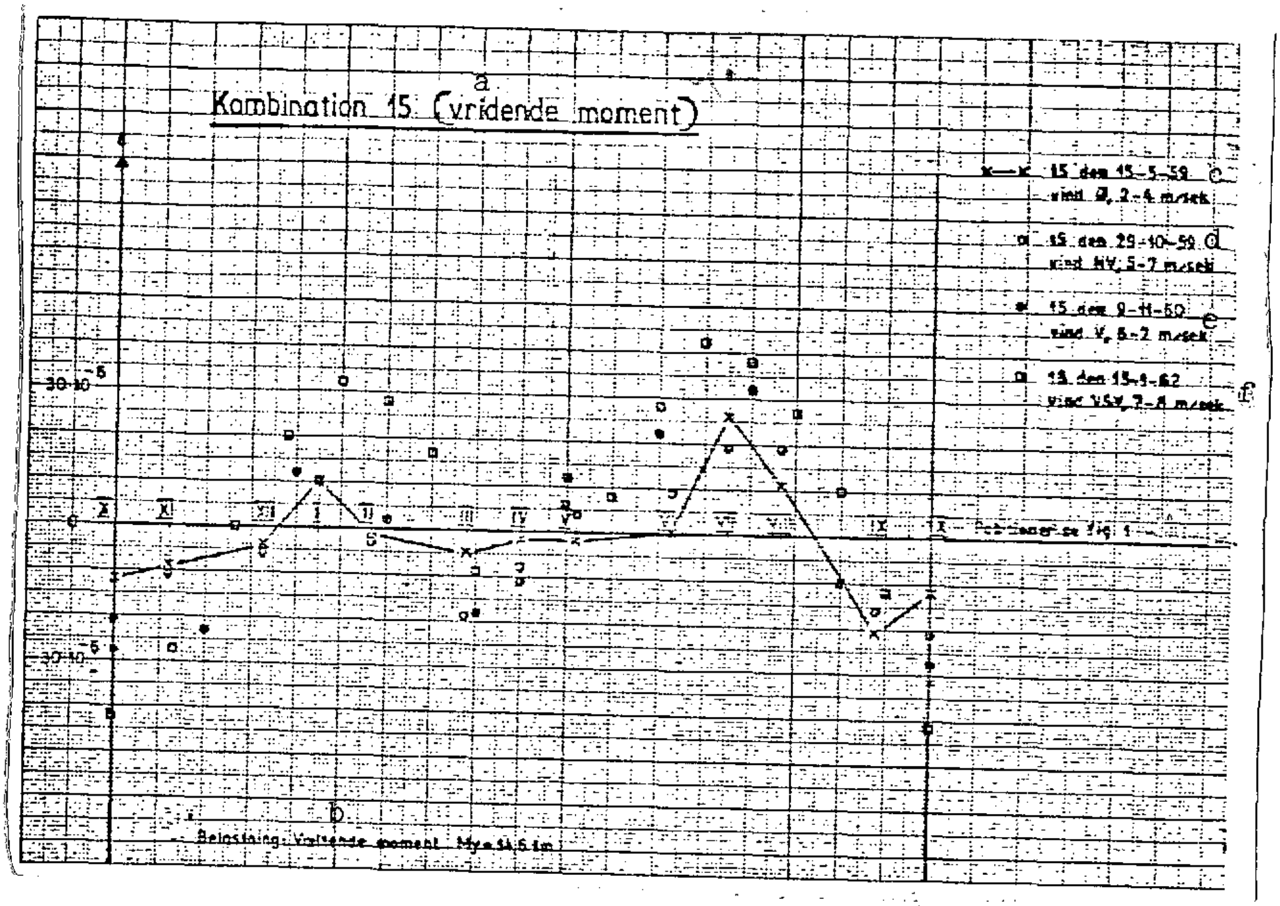


Fig. 31.

Key: a. Combination 15 (torsional moment)
b. Load: overturning moment M_y = 14.5 tm
c. 15 on 5/15/59, wind E, 2-4 m/sec
d. 15 on 10/29/59, wind NW, 5-7 m/sec
e. 15 on 11/9/60, wind W, 5-7 m/sec
f. 15 on 9/15/62, wind WSW, 7-8 m/sec
g. Positions, see Fig. 1

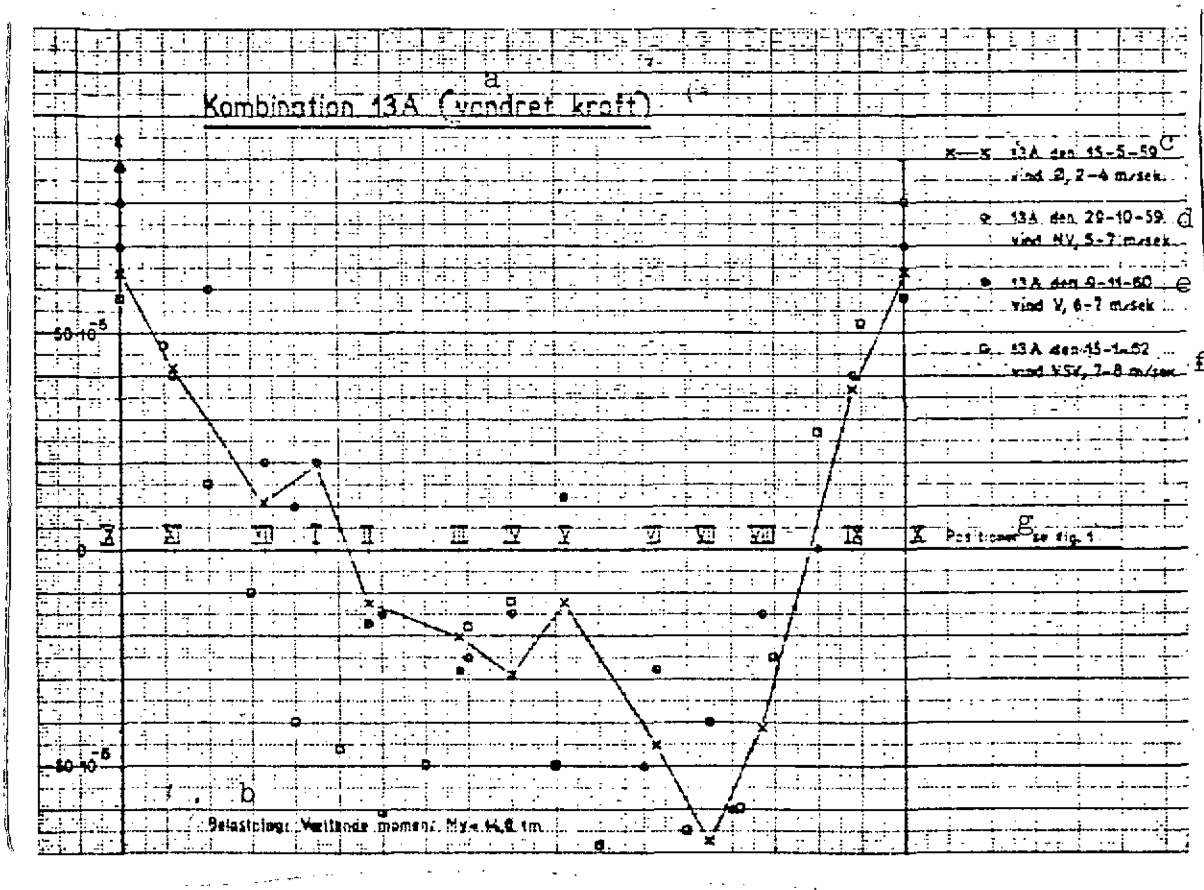


Fig. 32.

Key: a. Combination 13a (horizontal force)
b. Loading: overturning moment M_y = 14.6 tm
c. 13A on 5/13/39, wind E, 2-4 m/sec
d. 13A on 10/29/59, wind NW, 5-7 m/sec
e. 13A on 11/9/60, wind W, 6-7 m/sec
f. 13A on 1/15/62, wind WSW, 7-8 m/sec
g. Positions, see Fig. 1

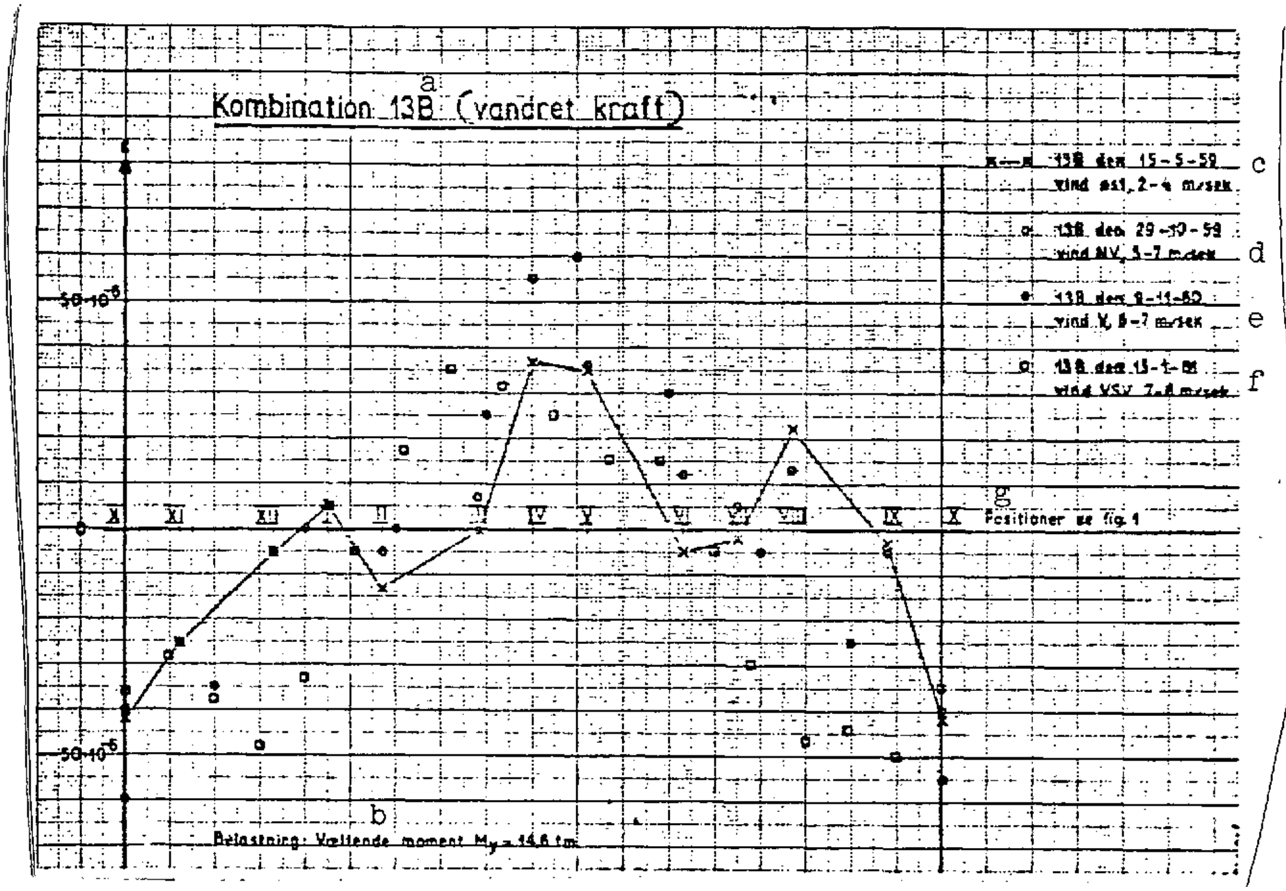


Fig. 33.

Key: a. Combination 13B (horizontal force)
b. Load: overturning moment M_y = 14.6 tm
c. 13B on 5/15/59, wind [illegible], 2-4 m/sec
d. 13B on 10/29/59, wind NW, 5-7 m/sec
e. 13B on 11/9/60, wind W, 5-7 m/sec
f. 13B on 1/15/62, wind WSW, 7-8 m/sec
g. Positions, see Fig. 1

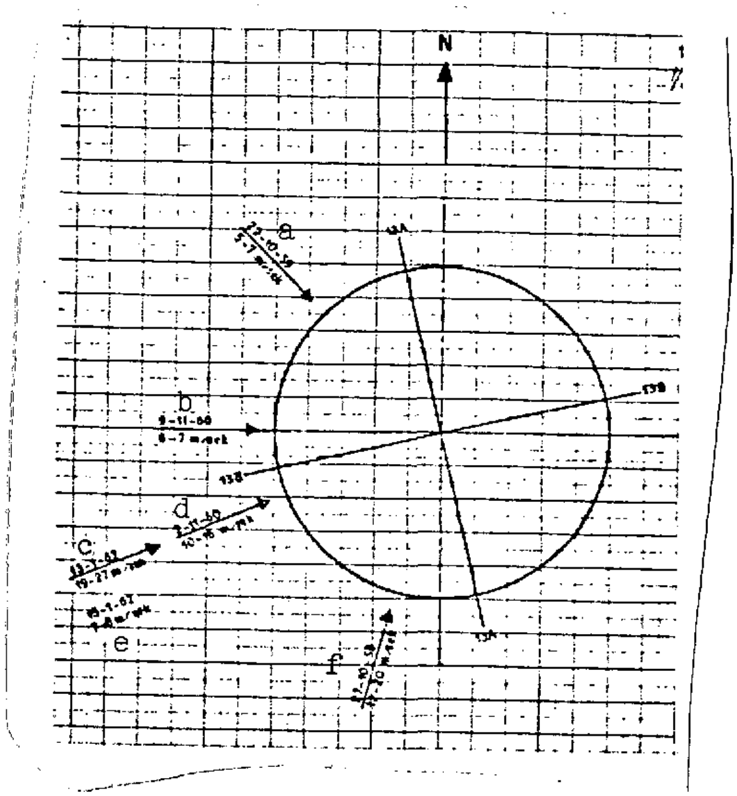


Fig. 34.

a. 10/22/59
b. 11/9/60
c. 1/13/62
d. 11/2/60
e. 1/15/62
f. 10/27/59

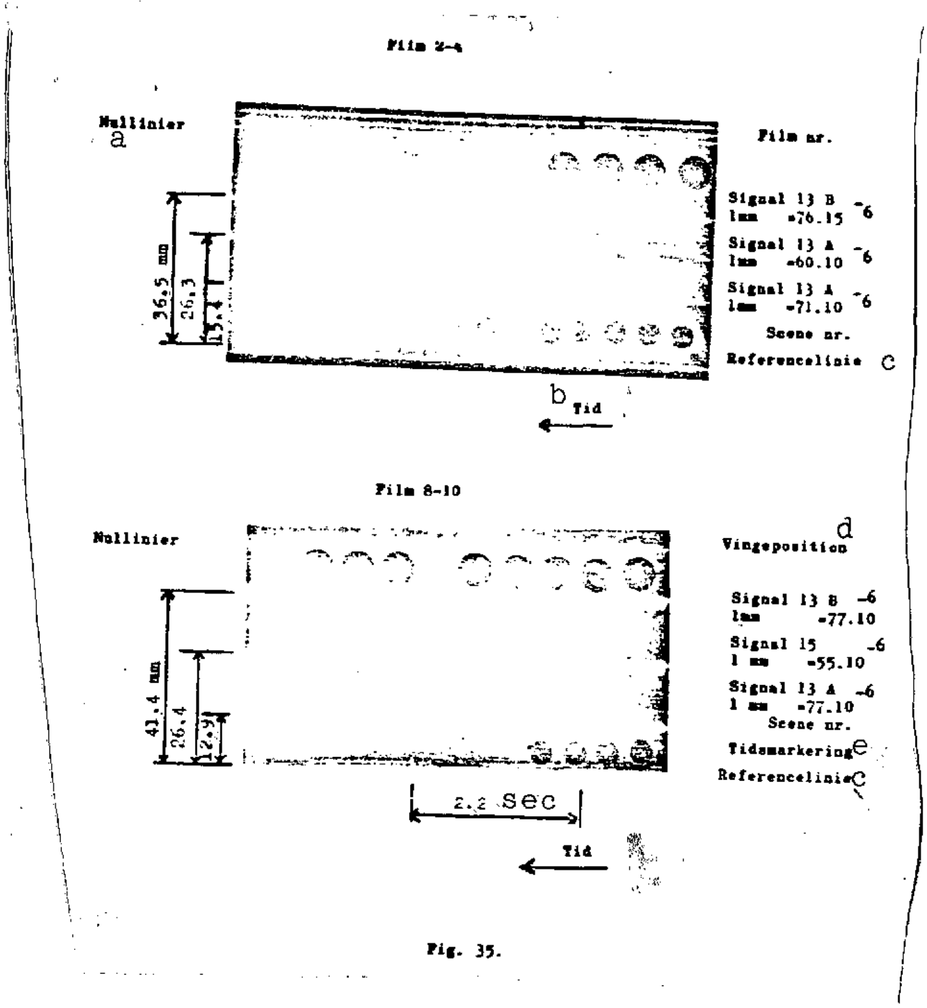


Fig. 35.

Key:
a. Zero lines
b. Time
c. Reference line
d. Sail position
e. Time marking

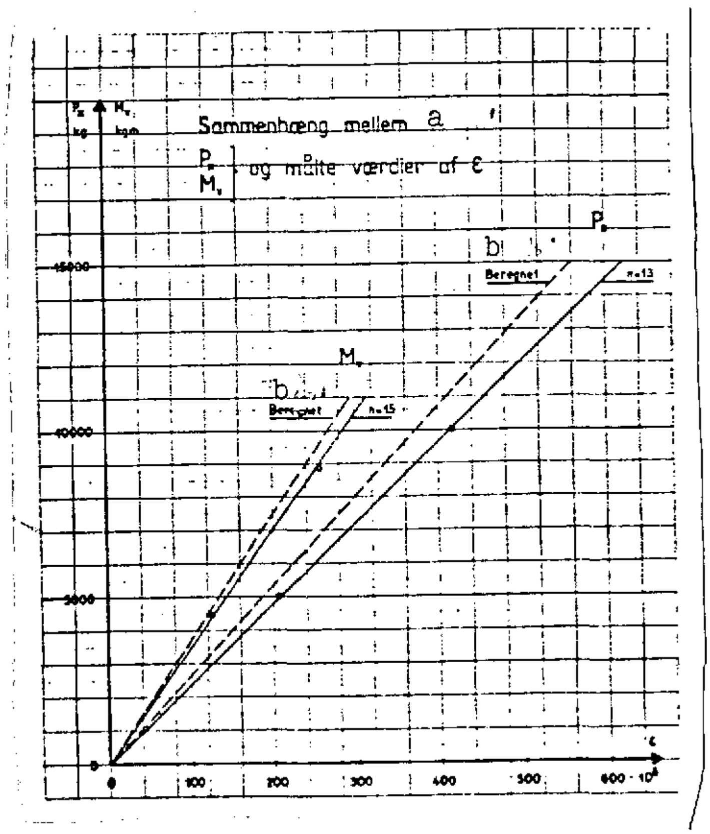


Fig. 36.

Key: a. Connection between $\left.\begin{matrix}P_x\\M_v\end{matrix}\right\}$ and measured values of ε
b. Calculated

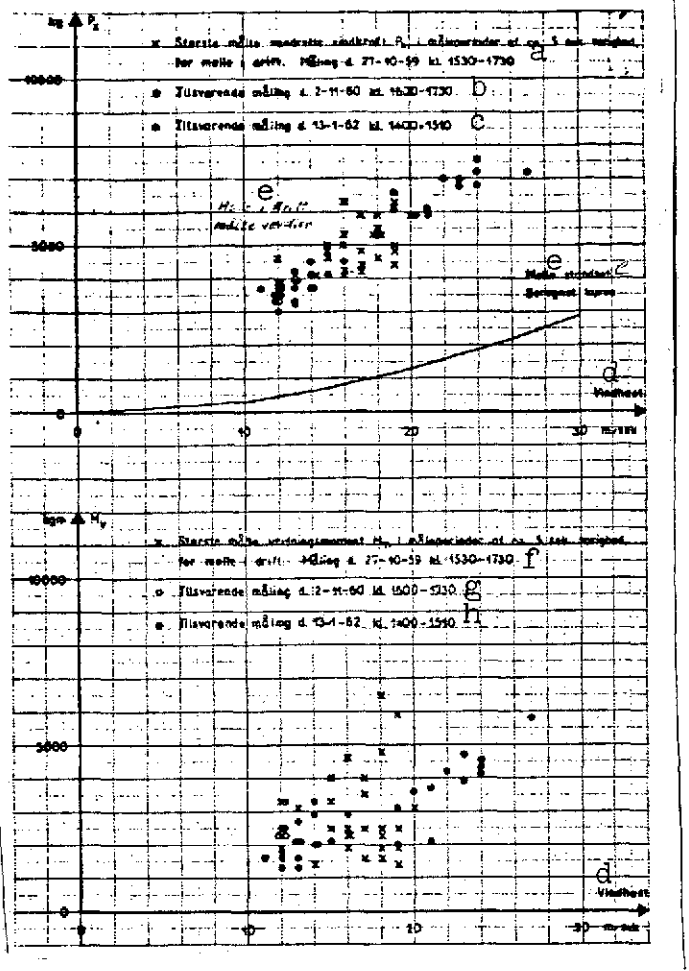


Fig. 37.

Key:

a. Largest measured horizontal wind energy P_x, in measurement intervals of approximately 5 sec duration, with the windmill in operation. Measurements dated 10/27/59, time 15:30-17:30

b. Corresponding measurements on 11/2/60, time 16:00-17:30

c. Corresponding measurements on 1/13/62, time 14:00-15:10

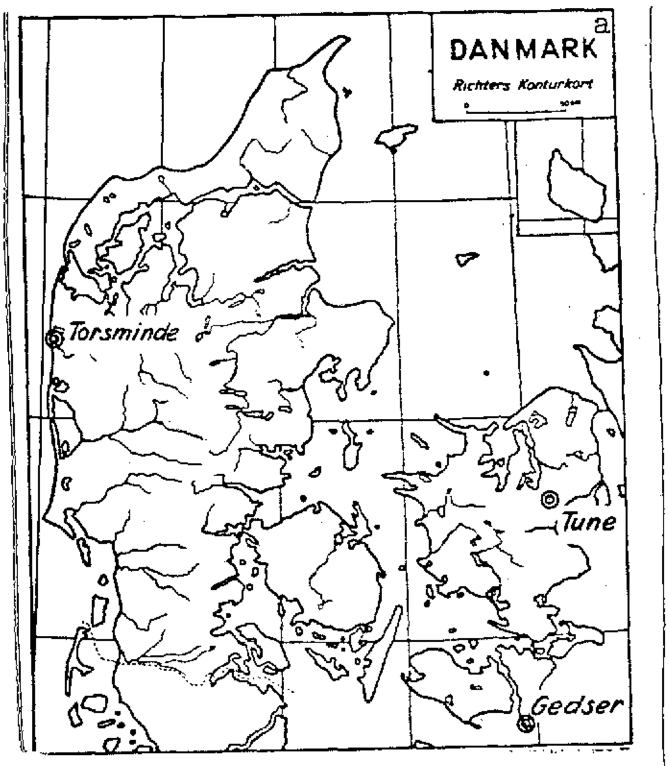
d. Wind speed

e. [illegible]

f. Greatest measurement torsional moment M[illegible], in measurement intervals of approximately 5 sec duration, with the windmill in operation. Measurements on 10/27/59, time 15:30-17:30

g. Corresponding measurements on 11/2/60, time 15:00-17:30

h. Corresponding measurements on 1/13/62, time 14:00-15:40



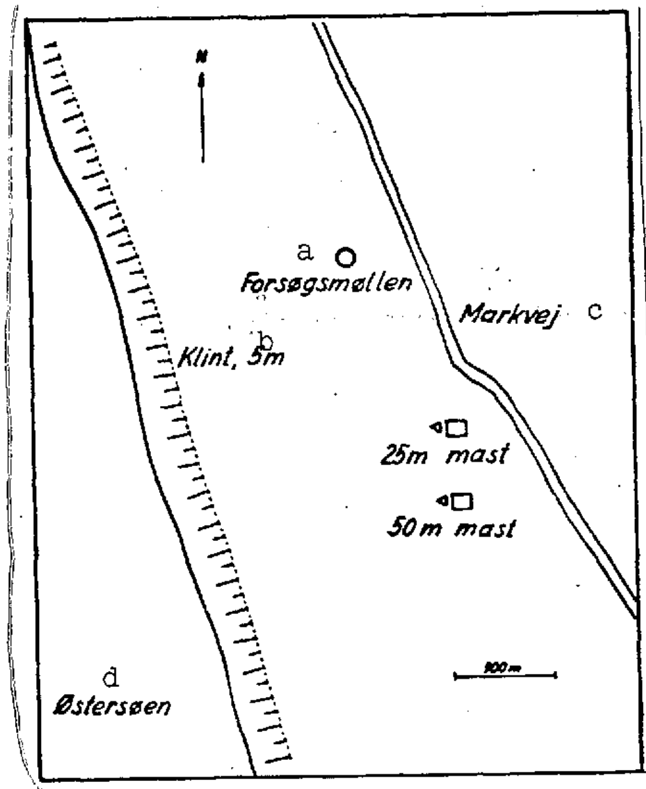


Fig. 38. Map of Denmark. 25 m high measuring stations for the wind are located in Tune and Torsminde. The test windmill is in Gedser, together with 25 m and 50 m high measuring stations for the wind.

Key: a. Denmark, Richter contour map

Fig. 39. The constructions at Gedser

Key: a. Test mill
b. Cliff, 5 m
c. Lane
d. Baltic Sea

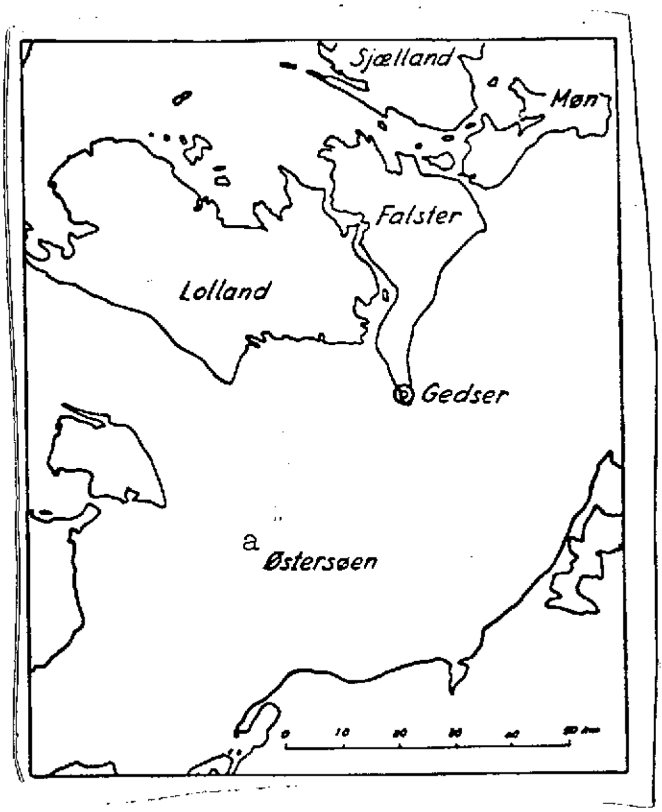


Fig. 40. Land and water areas around Gedser. The islands Lolland and Falster are low, open areas.

Key: a. Baltic Sea

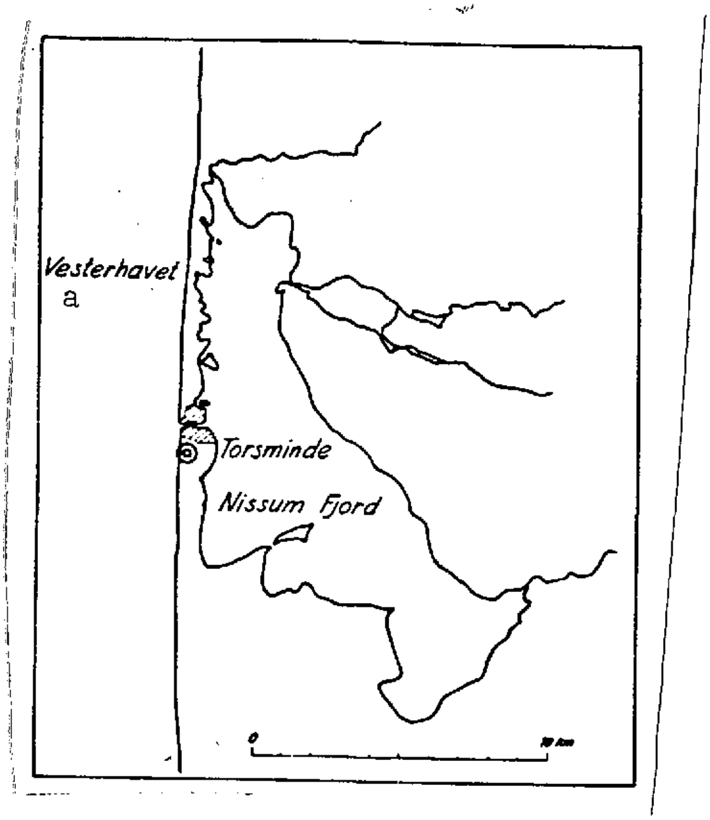


Fig. 41. Land and water areas around Torsminde. All of the land shown on the map is flat, under 40 m high.

Key: a. North Sea

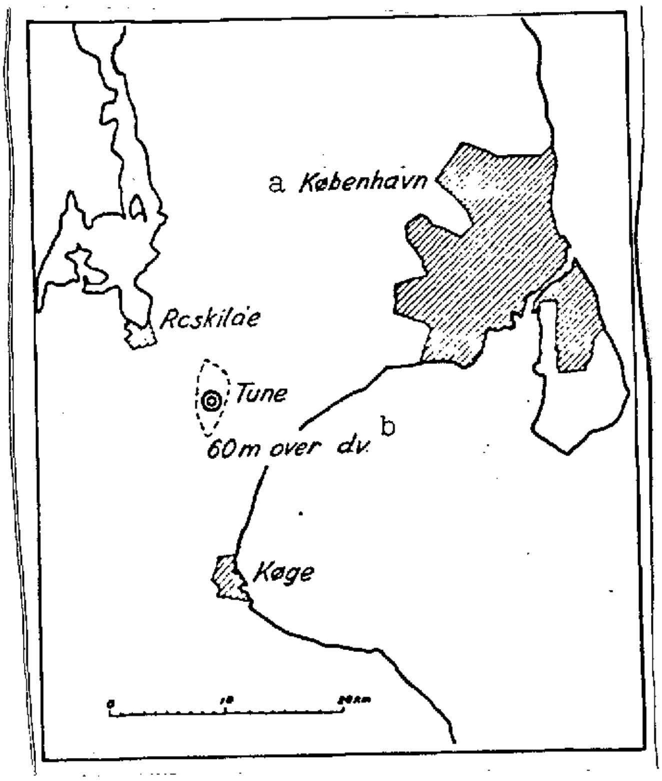


Fig. 42. Land and water areas around Tune.

Key: a. Copenhagen
b. Above sea level

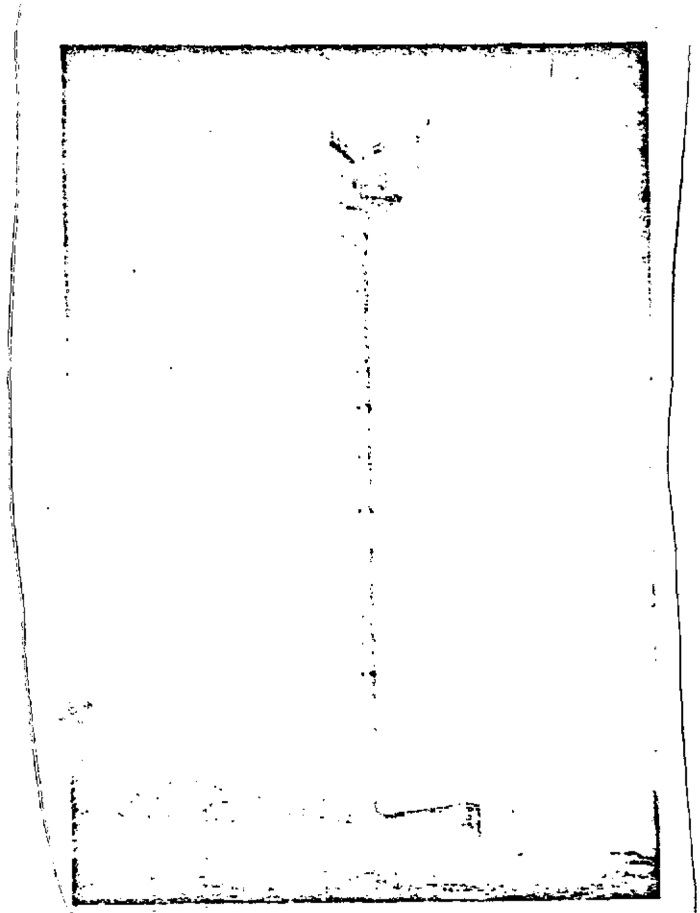
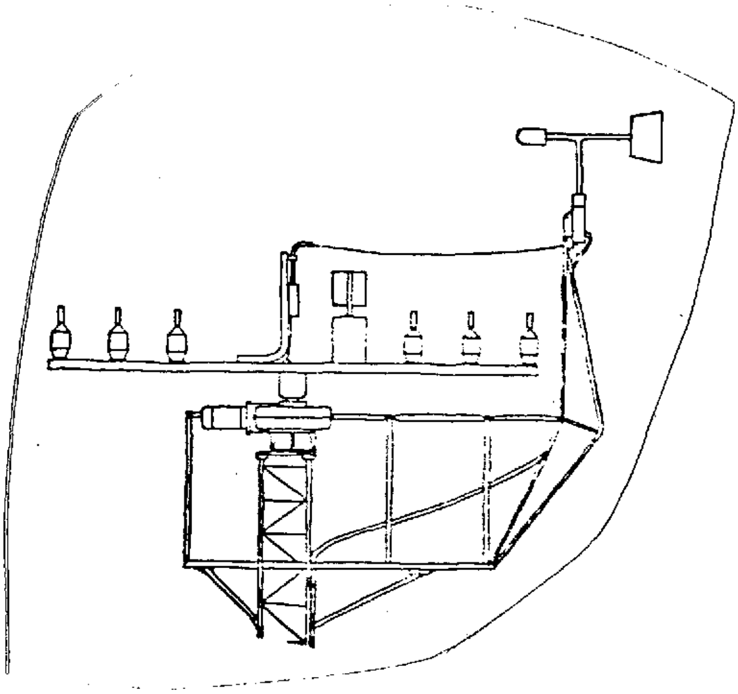


Fig. 43. Wind measuring station at Tune. The tower is 25 m high.



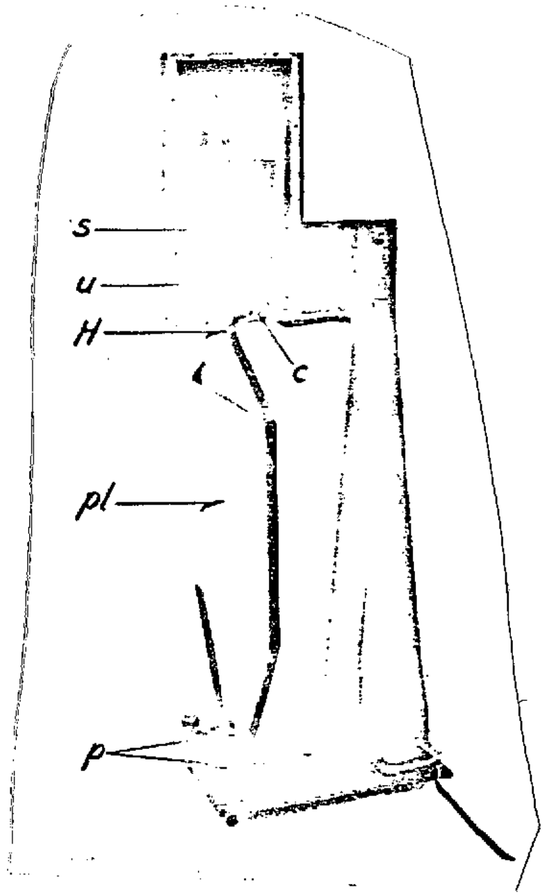


Fig. 44. Top of the tower. The sensors for the measurement of maximum stagnation pressure are to the right. The six sensors for power distribution are located on the horizontal beam, which is automatically rotated into the wind by an electrical motor with gears.

Fig. 45. Sensor for Ef-meter. s is the main spring. c is the contact point. pl is a plate, which can rotate about p.

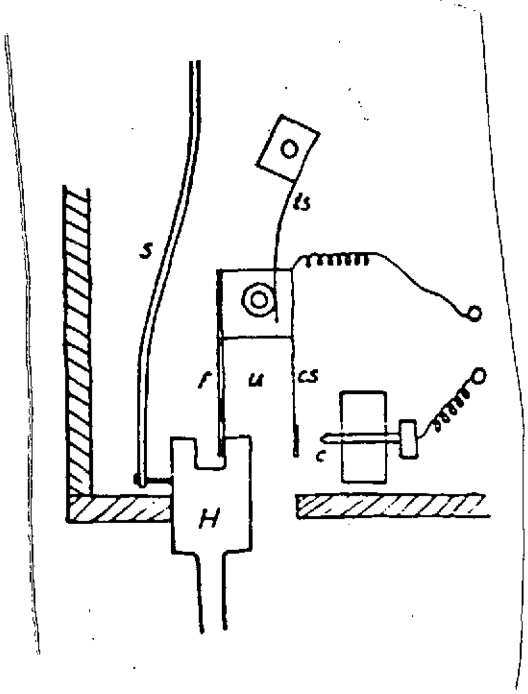


Fig. 46. Switch in Ef-meter.
ts is the friction spring.
c is the platinum contacts.
cs is the contact spring.
H is the top of the
movable plate.

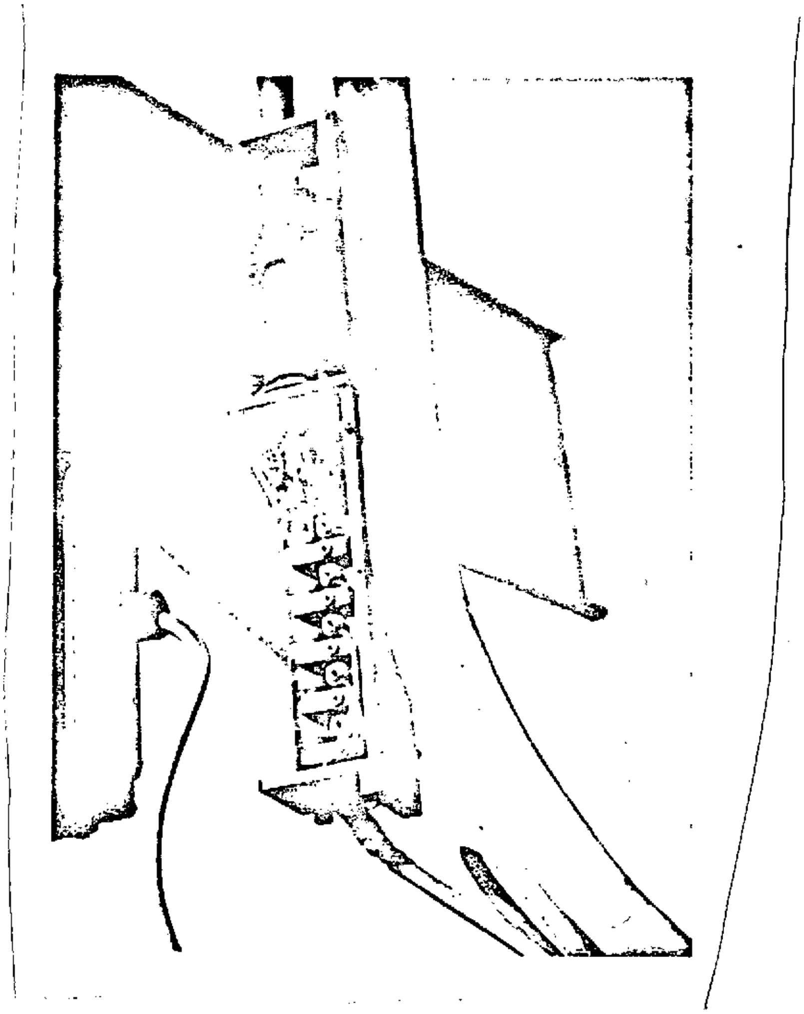


Fig. 47. Friction contacts for
the Ef-meter.

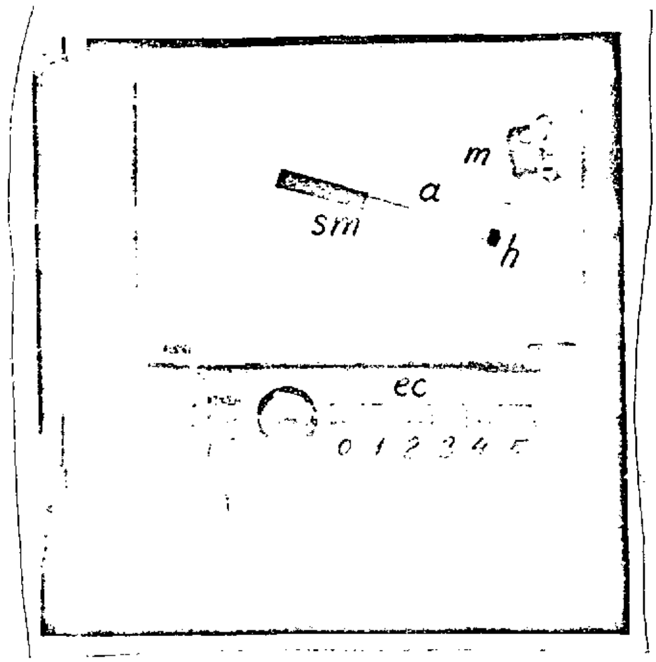


Fig. 48. Impulse generator and recorder of the Ef-meter. The head h is rotated by a synchronous motor sm and emits an impulse every 15 sec. The impulses are counted by the counters 0...6.

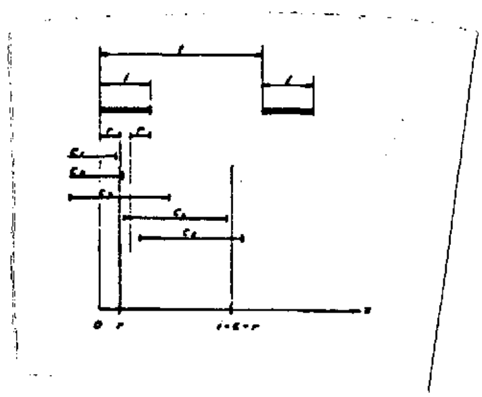


Fig. 49. i is the impulse time. t is the impulse distance. r is the counter's reaction time. c is the contact time. c1...c5 are the same contact times in five different instances.

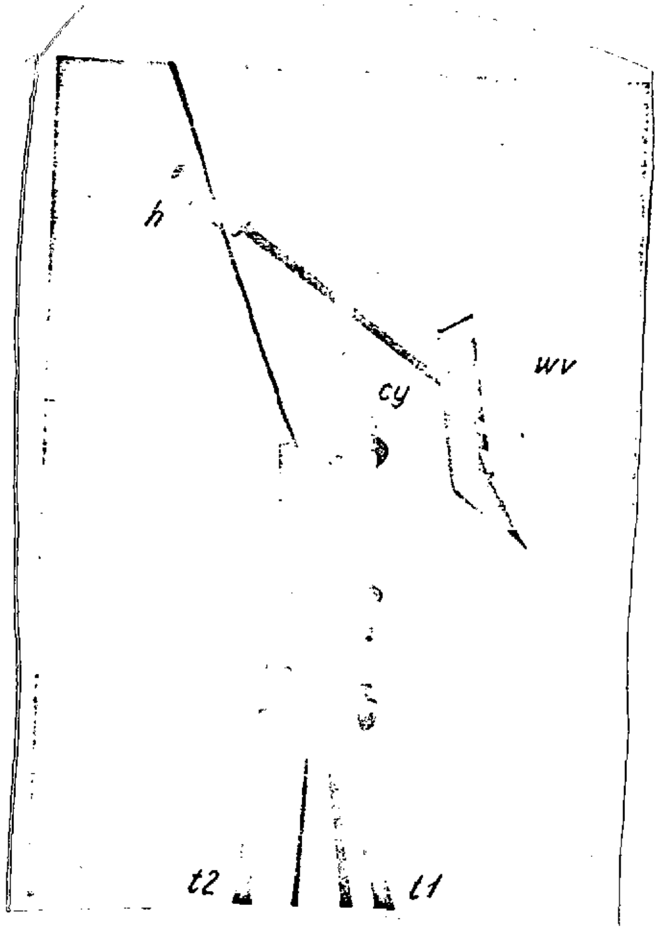


Fig. 50. Sensor for the q_{max}-meter. The wind's total pressure is received in the opening at h. The static pressure is received in the slits at cy. wv is the wind vane. The pressures are led down to the hut via t1 and t2.

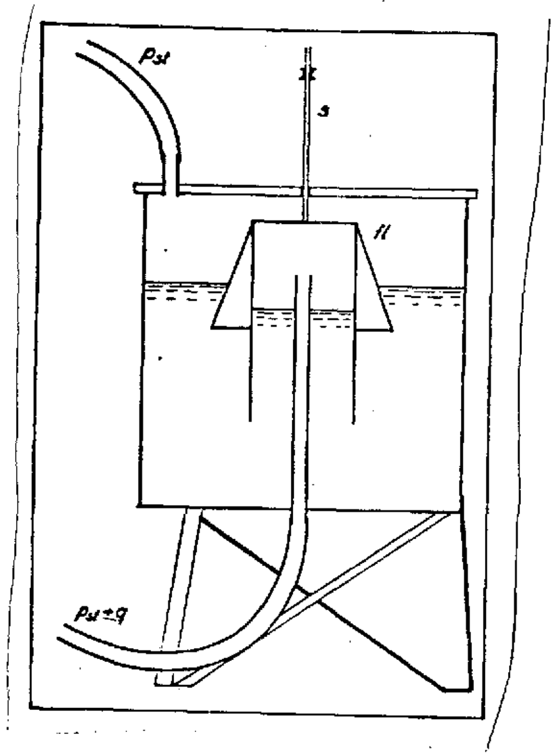


Fig. 51. Recorder for q_{max} measurements. The bell-shaped float fl is lifted by the wind's total pressure $p_{st} + q$ against the static pressure p_{st}, so that the virtual movement of the indicating rod s is a measurement of the stagnation pressure.

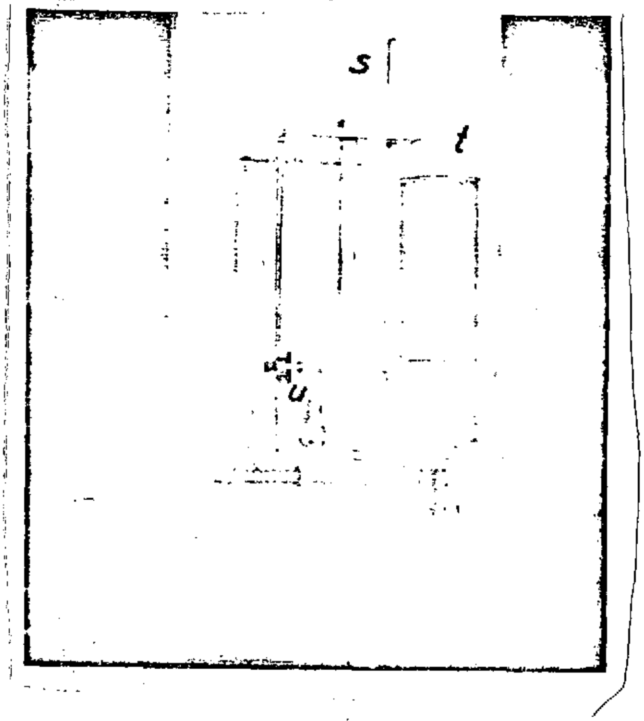


Fig. 52. Recorder for the q_{max} measurements. The float in Fig. 14 is steered by the rod s. sp is a writing point, which registers the stagnation pressure on the cylinder t. The cylinder is rotated forward every night slightly by the clock u. Otherwise it remains still.

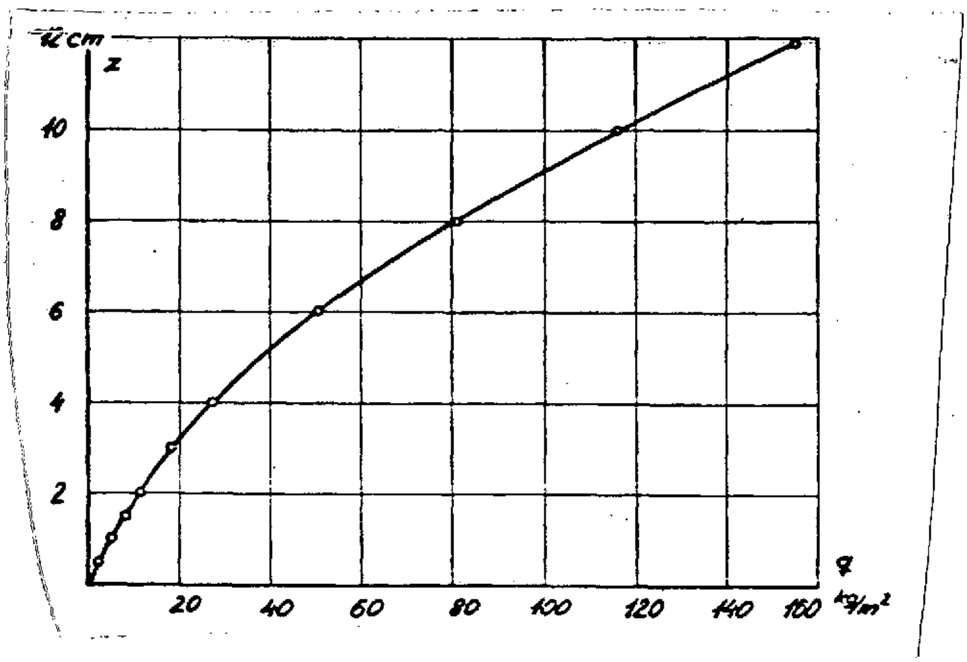


Fig. 53. Adjustment curve for q_{max} meter. The abscissa is the wind's stagnation pressure; the ordinate is the vertical motion of the writing point.

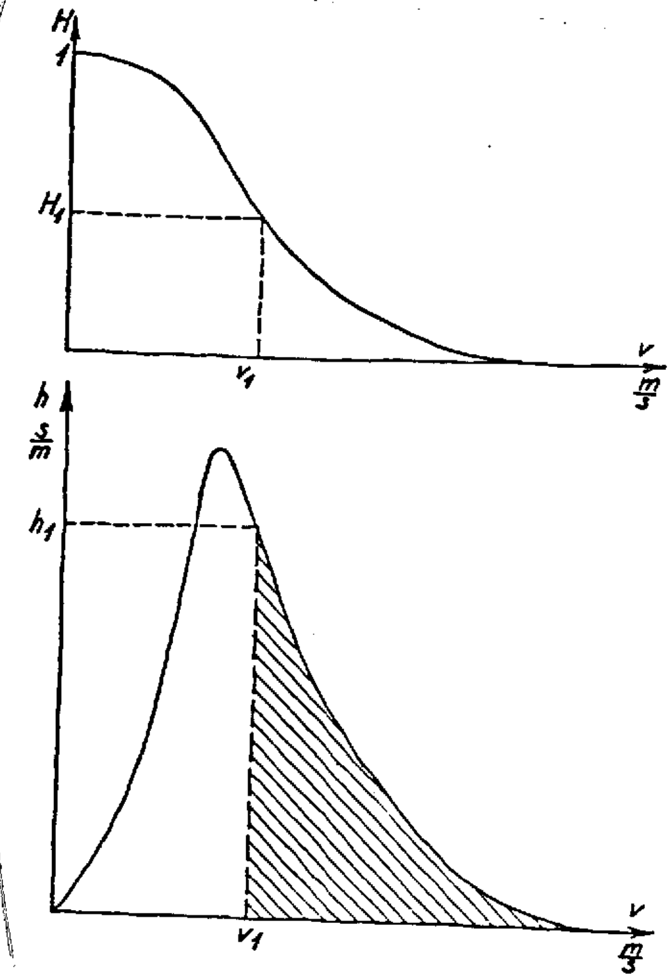


Fig. 54. The wind's accumulated frequency is shown above, directly as indicated by the Ef-meter. The wind frequency ddistribution is shown below.

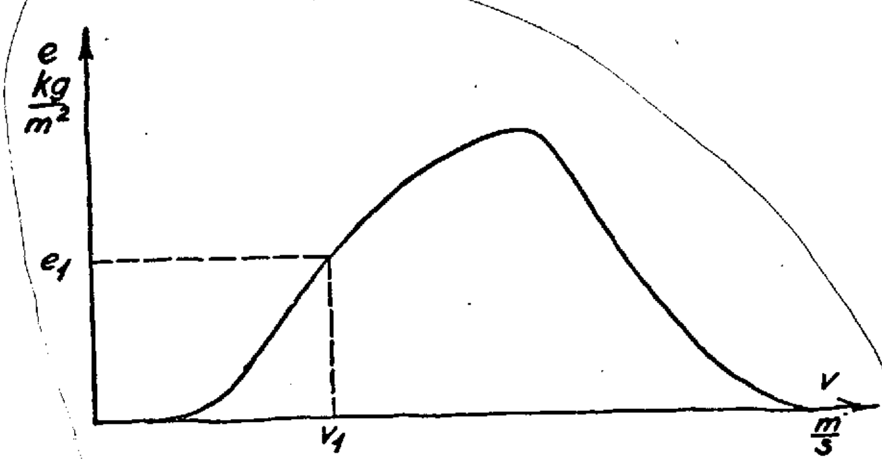


Fig. 55. Wind's power distribution.

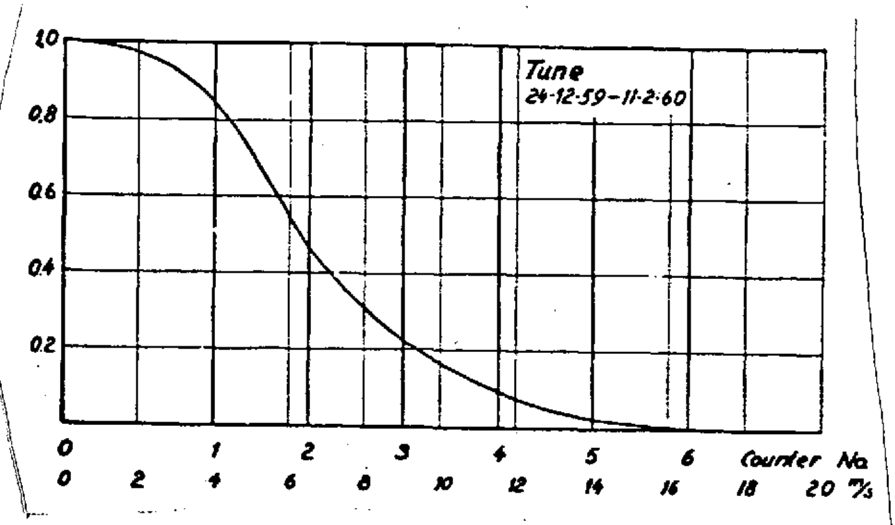


Fig. 56. The accumulated frequency of the wind at Tune in the period between December 24, 1959 and February 11, 1960. The absčissa is the wind speed in m/sec; the ordinate is dimensionless.

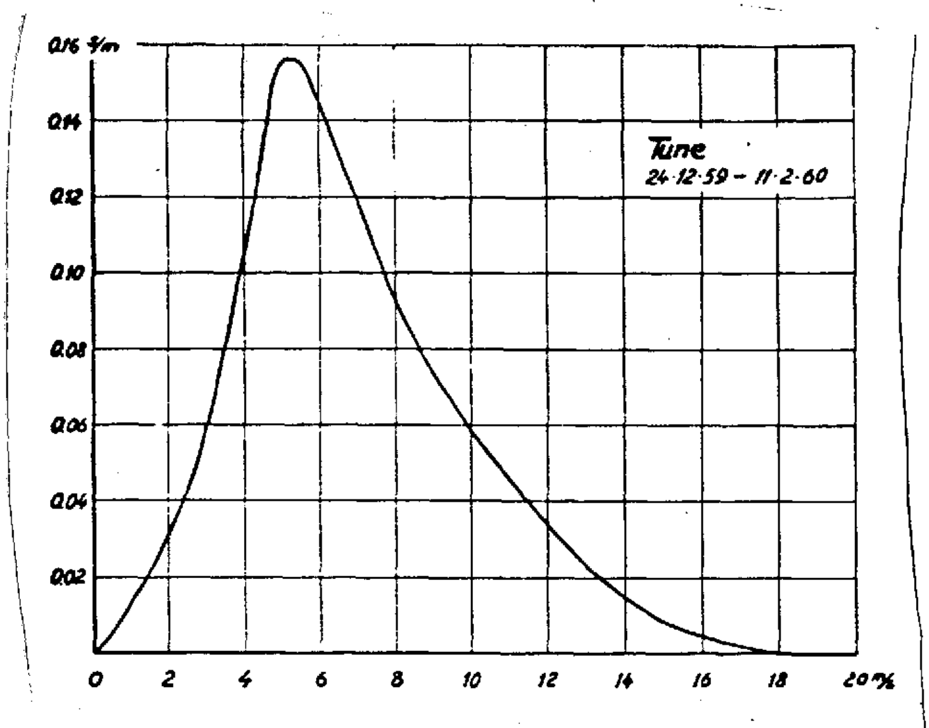


Fig. 57. Frequency distribution of the wind at Tune in the period from December 24, 1959 to February 11, 1960. The abscissa is the wind speed in m/sec; the ordinate has the dimensions sec/m.

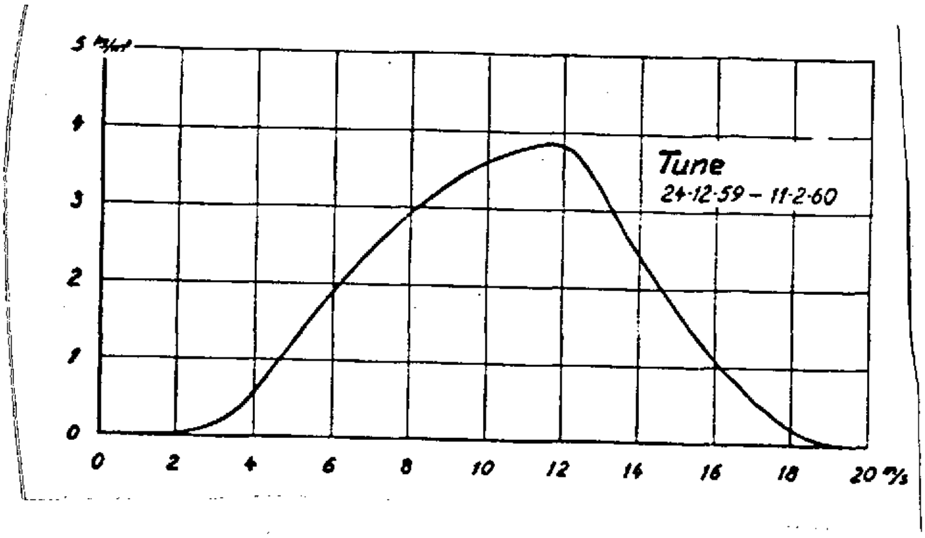


Fig. 58. Force distribution at Tune in the period between December 24, 1959 and February 11, 1960. The abscissa is the wind speed in m/sec; the ordinate is the wind's energy per unit of volume in kg/m².

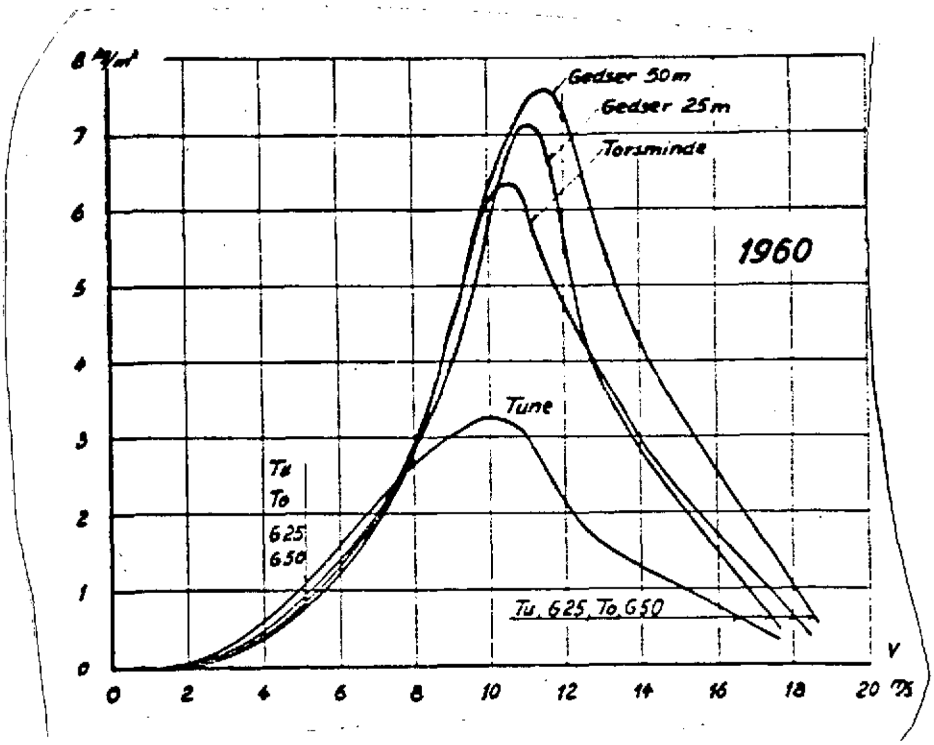


Fig. 59. Force distribution for the calendar year 1960 at the four stations. The abscissa is the wind's speed in m/sec; the ordinate is the wind's energy per unit of volume in kg/m².

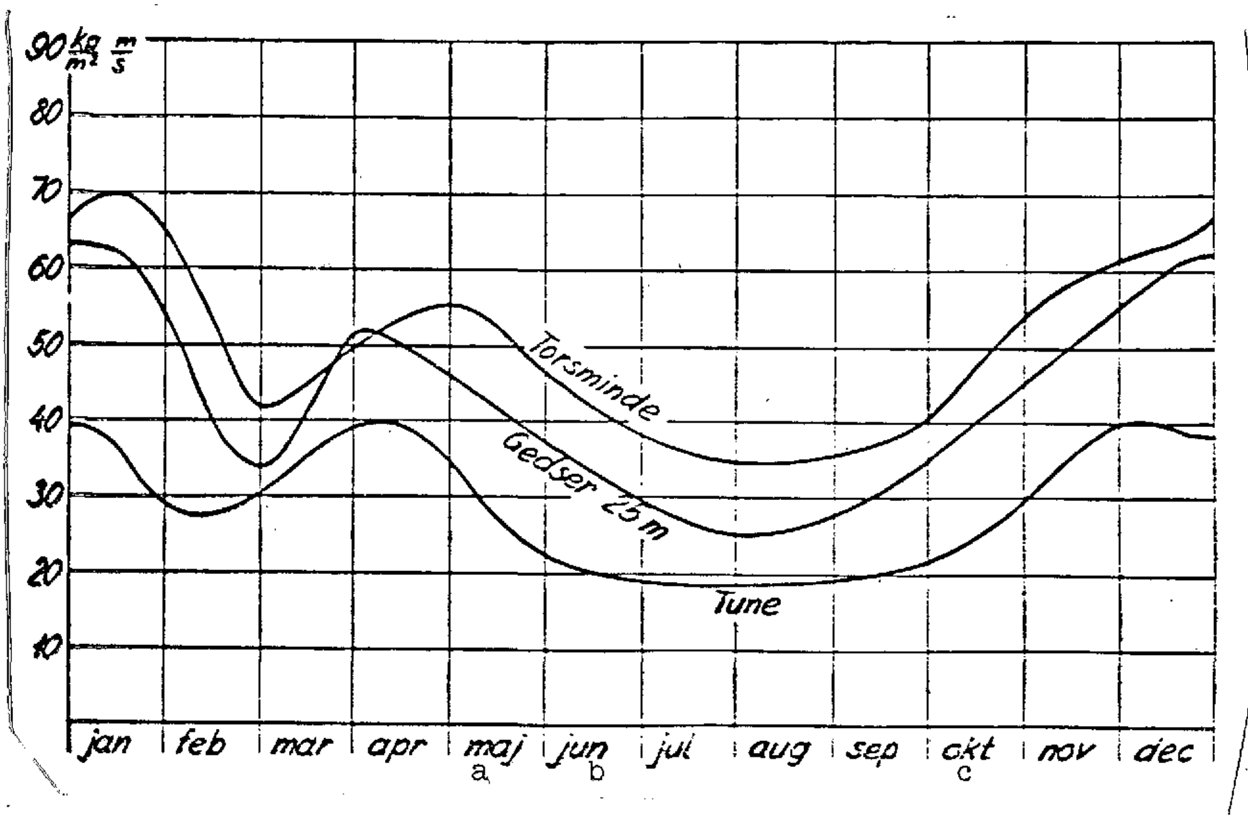


Fig. 60. Forces distribution over the year. The abscissa is the course of the year; the ordinate is the average power in (kg/m2)(m/sec).

Key: a. May
b. June
c. Oct.

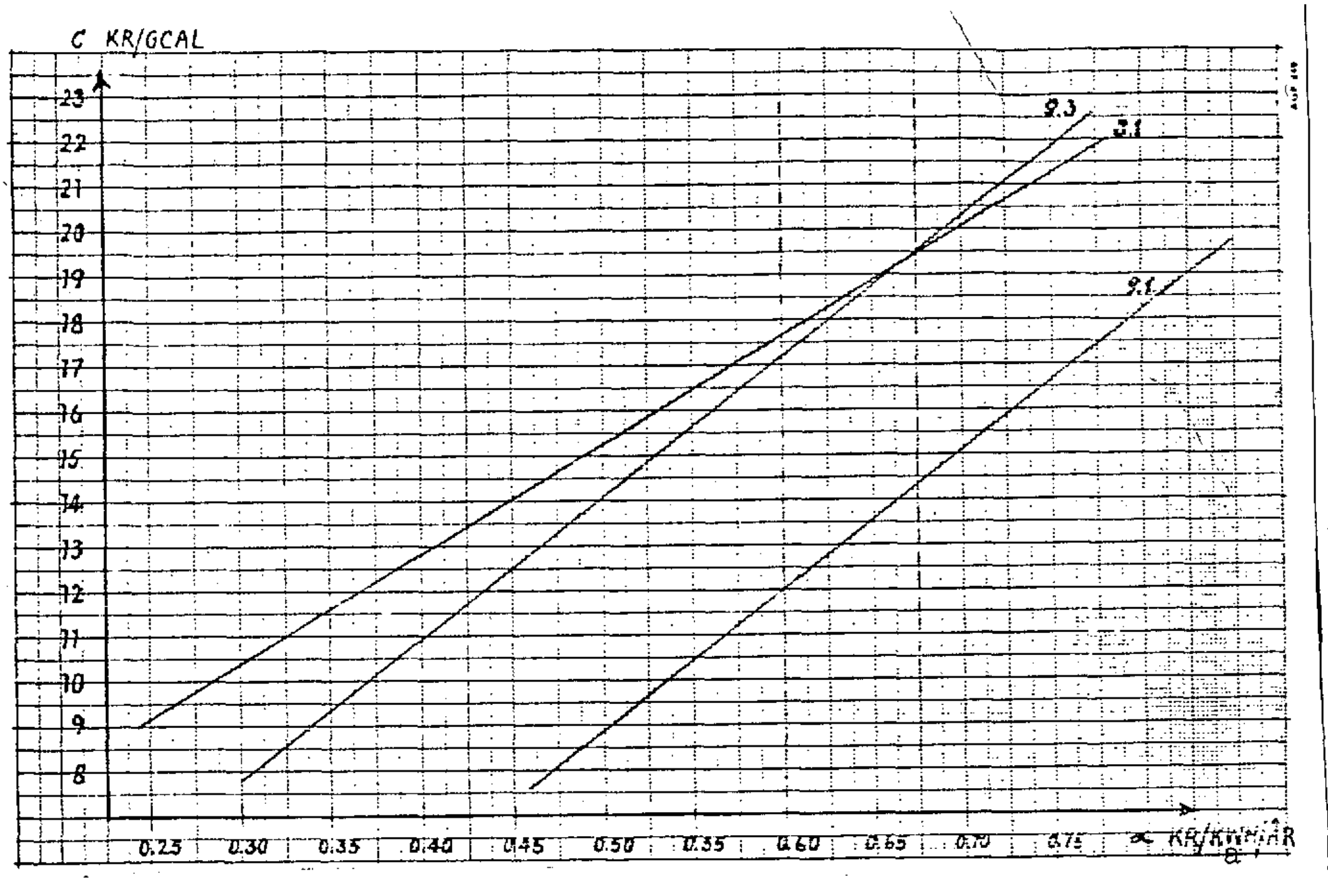


Fig. 61
Key: kr/kWh/year